This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.

+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.

+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.

+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`

NYPL RESEARCH LIBRARIES
3 3433 05775318 2

DESCHANEL'S
NATURAL PHILOSOPHY.

BY PROFESSOR EVERETT.

PART II: HEAT.

Mrd

Privat
3-PAE

Nrsl

Privat
3-PAE

Nrd

Privat
3-PAE

Presented to the Adelbert Library by Mr. D. C. Bridges

C

ELEMENTARY TREATISE

ON

NATURAL PHILOSOPHY.

BY

Augustin

A. PRIVAT DESCHANEL,

FORMERLY PROFESSOR OF PHYSICS IN THE LYCÉE LOUIS-LE-GRAND,
INSPECTOR OF THE ACADEMY OF PARIS.

TRANSLATED AND EDITED, WITH EXTENSIVE ADDITIONS,
BY J. D. EVERETT, M. A., D. C. L., F. R. S. E.,
PROFESSOR OF NATURAL PHILOSOPHY IN THE QUEEN'S COLLEGE, BELFAST.

IN FOUR PARTS.

PART II.—HEAT.

ILLUSTRATED BY ONE HUNDRED AND FIFTY-ONE ENGRAVINGS ON WOOD.

NEW YORK:
D. APPLETON AND COMPANY,
549 BROADWAY.

34249
ASTOR LIBRARY
JUN
8
1895
NEW YORK

In the present volume, the chapter on Thermo-dynamics is almost entirely the work of the Editor. Large portions of the chapters on Conduction and on Terrestrial Temperatures have also been re-written; and considerable additions have been made in connection with Hygrometry, the Theory of Exchanges, the Specific Heats of Gases, and the Motion of Glaciers. Minor additions and modifications have been numerous, and will easily be detected by comparison with the similarly numbered sections in the original.

The nomenclature of units of heat which has been adopted, is borrowed from Prof. G. C. Foster's article "Heat" in Watts' *Dictionary of Chemistry*.

CONTENTS—PART II.

HEAT.

CHAPTER XIX. THERMOMETRY.

Heat.—Cold.—Temperature.—Expansion produced by heat.—Choice of thermometric substance.—Construction of mercurial thermometer.—Fixed points.—Thermometric scales.—Change of zero.—Value of a degree.—Sensibility.—Weight thermometer.—Alcohol thermometer.—Self-registering thermometers.—Six's.—Rutherford's.—Phillips'.—Negretti's.—Walferdin's.—Sea and well thermometers.—Protection against pressure of water.—Thermograph.—Metallic thermometers.—Secchi's meteorograph.—Pyrometers.—Differential thermometers, ... pp. 241–263

CHAPTER XX. FORMULÆ RELATING TO EXPANSION.

Expansion.—Expansion factor.—Coefficient of expansion.—Cubic, linear, and superficial expansion.—Comparison of volumes and densities at different temperatures.—Correction of specific-gravity for temperature.—Gases, ... pp. 264–268.

CHAPTER XXI. EXPANSION OF SOLIDS.

Experiments of Laplace and Lavoisier.—Method of Ramsden and Roy.—Compensated pendulums.—Force of expansion of solids, ... pp. 269–274.

CHAPTER XXII. EXPANSION OF LIQUIDS.

Relation between apparent and absolute expansion.—Expansion of glass.—Expansion of any liquid.—Maximum density of water.—Saline solutions.—Absolute expansion of mercury.—Expansion of iron and platinum.—Convection of heat in liquids.—Heating buildings by hot water.—Oceanic currents, ... pp. 275–286.

CHAPTER XXIII. EXPANSION OF GASES.

Gay-Lussac's experiments.—Regnault's experiments.—Air-thermometer.—Absolute temperature and absolute zero.—Regnault's pyrometer.—Density of gases, absolute and relative.—Experimental determination.—Weight of a litre of air.—Table of densities of gases.—Draught of chimneys.—Stoves and fire-places, ... pp. 287–301.

CHAPTER XXIV. FUSION AND SOLIDIFIC[illegible]

[illegible] Latent heat.—Heat of fu [illegible] —Solution.—
[illegible] fficulty of making a [illegible] ent.—Cooling
[illegible] flowers.—Super [illegible] udden con-

gelation.—Change of volume in congelation.—Expansive force of freezing water.—Melting-point raised or lowered by hydrostatic pressure.—Effect of stress in solids upon melting and solution.—Regelation.—Apparent plasticity of ice.—Motion of glaciers, ... pp. 302–316.

CHAPTER XXV. EVAPORATION AND CONDENSATION.

Spontaneous evaporation.—Vapours and permanent gases.—Vapours at maximum density and tension, or saturated vapours.—Maximum density and tension depend on temperature.—Effect of presence of gas or of another vapour.—Dalton's two laws.—Liquefaction of gases.—Faraday's first method.—Thilorier's apparatus.—Bianchi's—Faraday's later method.—Continuous transition from gas to liquid or from liquid to gas.—Experiments of Cagniard de la Tour, Drion, and Andrews.—Critical temperature.—Latent heat of evaporation.—Cooling by evaporation.—Causing water to freeze.—And mercury.—Carré's two forms of apparatus for making ice.—Cryophorus.—Solidification of gases, ... pp. 317–333.

CHAPTER XXVI. EBULLITION.

Phenomena of ebullition.—Definite temperature.—Constancy of temperature.—Tension of vapour.—Theory of ebullition.—Effect of pressure on boiling-point.—Franklin's experiment.—Determination of heights by boiling-point.—Hypsometer.—Papin's digester.—Safety-valve.—Boiling-point of saline solutions.—Temperature of vapour evolved.—Boiling-point of mixtures.—Difficulty of making a beginning without air.—Experiments of Donny and Dufour.—Spheroidal state.—Freezing of mercury in red-hot crucible.—Cause of the spheroidal state.—Distillation.—Conditions of rapid evaporation, ... pp. 334–348.

CHAPTER XXVII. MEASUREMENT OF TENSION AND DENSITY OF VAPOURS.

Importance in connection with steam-engine.—Dalton's experiments on maximum tensions of aqueous vapour.—Regnault's two methods of experiment.—Table of results.—Representation by curve and empirical formulæ.—Vapours of other liquids.—Expression of tensions in absolute measure.—Laws of combination by volume.—Relation of vapour-densities (not maximum) to chemical equivalents.—Meaning of "vapour-density" of a substance.—Dumas' method of determining vapour-densities.—Example.—Table of vapour-densities.—Limiting values as temperature increases.—Gay-Lussac's method.—Volume of a given weight of steam, ... pp. 349–363.

CHAPTER XXVIII. HYGROMETRY.

Technical meaning of "humidity."—Dew-point.—Hygroscopes.—Hygrometers.—De Saussure's.—Dew-point instruments.—Leroy's.—Daniell's.—Regnault's.—Wet and dry bulb.—Glaisher's factors.—Apjohn's formula, and discussion of the basis on which it rests.—Chemical hygrometer.—Weight of given volume of moist air.—Volume of saturated air.—Aqueous meteors.—Cloud and mist.—Supposed vesicles.—Howard's nomenclature of clouds.—Causes of formation of cloud.—Rain.—Rain-gauge.—Annual rain-fall.—Snow and hail.—Snow-crystals, ... pp. 364–384.

CHAPTER XXIX. RADIANT HEAT.

Radiation.—Characteristics of.—Newton's law of cooling.—Dulong and Petit's law of cooling.—Law of inverse squares.—Experimental proof.—Laws of reflection.—Burning-

mirrors.—Conjugate mirrors.—Reflecting, diffusive, absorbing, and transmissive powers.—Coefficients of emission and absorption equal.—Absolute value of coefficient of radiation for lamp-black.—Different kinds of heat-ray.—Theory of exchanges.—Thermopile.—Experimental comparison of emissive powers.—And of absorbing powers.—Tables of results.—Variation of absorption with source of heat.—Determination of reflecting powers.—And diffusive powers.—Diathermancy.—Experimental measurement.—Table of heat transmitted by different substances.—Diathermancy and transparency.—Iodine in sulphide of carbon.—Rock-salt.—Diathermancy of gases.—Remarkable effect of scents and of aqueous vapour.—Influence of thickness of plate upon amount of absorption.—Connection between radiant heat and light.—Fluorescence and calorescence.—Selective emission and absorption.—Their equality.—Proof from reversal of bright lines in spectrum.—Dew, ... pp. 385–413.

CHAPTER XXX. CONDUCTION OF HEAT.

Conduction described and distinguished from radiation.—Variable stage and permanent state.—Influence of specific heat.—Definition of conductivity.—Mathematical note on conduction during variable stage.—Experiments to illustrate differences of conductivity.—Ingenhousz's apparatus.—Metals the best conductors.—Wire-gauze and Davy lamp.—Domestic applications.—Experimental determination of conductivity.—Table of results obtained by Wiedemann and Franz.—Forbes' determination of absolute conductivity of iron.—Absolute conductivity of rock deduced from underground temperatures.—Conduction in liquids.—Despretz's experiment on water.—Professor Guthrie on conducting power of water.—Small conducting power of gases.—Accounts for warmth of cloth, &c.—Norwegian cooking-box.—Conductivity of hydrogen, . pp. 414–425.

CHAPTER XXXI. CALORIMETRY.

Test of equal quantity.—Units of heat, gramme-degree, pound-degree, &c.—Thermal capacity, or water equivalent.—Specific heat, or capacity per unit mass.—Capacity per unit volume.—Experiment to illustrate differences of specific heat.—Measurement of specific heat by fusion of ice.—Method of mixtures.—Note on temperature of mixtures.—Calculation of experiment, with corrections.—Regnault's apparatus.—Table of specific heats.—Great specific heat of water.—Effect on climate.—Dulong and Petit's law.—Equal thermal capacities of all atoms.—Specific heat of gases, at constant pressure, and at constant temperature.—Their laws.—Specific heat of air.—Ratio of the two specific heats.—Changes of volume, pressure, and temperature when no heat enters or escapes.—Latent heat of fusion.—Table of latent heats, and of specific heats in the two states.—Latent heat of evaporation.—Despretz's apparatus.—Regnault's experiments.—Tables of results.—Heat of chemical combination.—Apparatus of Favre and Silbermann, Dulong, Andrews.—Table of heats of combustion.—Oxy-hydrogen blowpipe, pp. 426–444.

CHAPTER XXXII. THERMO-DYNAMICS.

Connection between heat and work.—Caloric theory. Heat developed in compression and in friction.—Rumford experiments on the boring of cannon.—Davy's experiment on friction of ice.—Recent investigators.—Foucault's electro-magnetic apparatus.—Determination of Joule's equivalent.—First law of thermo-dynamics.—Illustrations from railway trains, cannon-balls, &c.—Heat lost in expansion of gases.—Joule's experiment on expansion without external work.—Calculation of difference between the two specific heats.—True specific heat of a gas.—Thermic engines.—Definition of efficiency.—Carnot's principles.—Reversibility a test of maximum efficiency.—Second law of thermo-dynamics, with appendices.—A scale of temperature independent of the selec-

tion of any particular substance.—Heat required for passing from one given state to another not a constant quantity.—Work done against external pressure in expansion. —Calculation of lowering of melting-point by pressure.—Calculations relating to liquids at temperatures below melting-point.—Animal heat and work.—Chemical combination. —Vegetable growth.—Coal.—Solar heat.—Its sources.—Meteoric theory.—Contraction theory, ... pp. 445–466.

CHAPTER XXXIII. STEAM AND OTHER HEAT ENGINES.

Heat-engines in general.—Air-engine.—History of steam-engine.—Watt's single-acting engine.—Double-acting engine.—Slide-valve.—Eccentric.—Exhaust-pump.—Governor-balls.—Fly-wheel.—Working expansively.—Compound engines.—Surface condensation.—Classification of steam-engines.—High and low pressure.—Condensing and non-condensing.—Work obtained with and without expansion.—Superheating.—Oscillating cylinders.—Example of high-pressure engine.—Rotatory engine.—Boilers.—Safety-valve and gauges.—Causes of explosions.—Giffard's injector.—Locomotive, its history. —Description.—Link-motion for reversing.—Gas engines, ... pp. 467–492.

CHAPTER XXXIV. TERRESTRIAL TEMPERATURES.

Temperature of the air.—Mean temperature of a day.—Mean annual temperature.— Isothermal lines.—Insular and continental climates.—Underground temperature.— Temperature upwards in the air.—Cooling of air by ascent.—Causes of winds.—Land and sea breezes.—Monsoons.—Trade-winds.—Effect of earth's rotation.—General circulation of air over the earth.—Centrifugal theory of atmospheric distribution.— Indraught along earth's surface towards the poles.—Origin of cyclones.—Anemometers, ... pp. 493–504.

TABLE OF CONSTANTS.

The pressure of one atmosphere, or 760 millimetres (29·922 inches) of mercury, is 1·033 kilogramme per square centimetre, or 14·73 lbs. per sq. inch.

The weight of a litre of dry air, at this pressure (at Paris) and 0° C., is 1·293 gramme.

Dry air at constant pressure expands by ·003665 (or $\frac{1}{273}$) of its volume at 0° C., for each degree Cent.

The specific heat of dry air at constant pressure is ·2375.

The specific heat of dry air at constant volume is ·168.

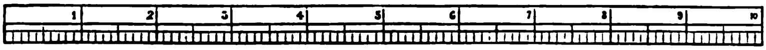
The ratio of these numbers is 1·41, and their difference ·0695.

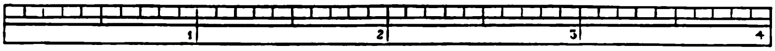
The latent heat of fusion of ice is 79°·25 C.

The latent heat of steam at one atmosphere is 537° C.

FRENCH AND ENGLISH MEASURES.

A DECIMETRE DIVIDED INTO CENTIMETRES AND MILLIMETRES.





INCHES AND TENTHS.

TABLE FOR THE CONVERSION OF FRENCH INTO ENGLISH MEASURES.

MEASURES OF LENGTH.

1 Millimetre = ·03937079 inch, or about $\frac{1}{25}$ inch.
1 Centimetre = ·3937079 inch.
1 Decimetre = 3·937079 inches.
1 Metre = 39·37079 inches, or 3·2809 feet nearly.
1 Kilometre = 39370·79 inches, or 1093·6 yards nearly.

MEASURES OF AREA.

1 sq. millimetre = ·00155006 sq. inch.
1 sq. centimetre = ·155006 sq. inch.
1 sq. decimetre = 15·5006 sq. inches.
1 sq. metre = 1550·06 sq. inches, or 10·7643 sq. feet.

MEASURES OF VOLUME.

1 cubic centimetre = ·0610271 cubic inch.
1 cubic decimetre = 61·0271 cubic inches.
1 cubic metre = 61027·1 cubic inches, or 35·3166 cubic feet.

The Litre (used for liquids) is the same as the cubic decimetre, and is equal to 1·76172 imperial pint, or ·220215 gallon.

MEASURES OF WEIGHT (or MASS).

1 milligramme = ·015432349 grain.
1 centigramme = ·15432349 grain.
1 decigramme = 1·5432349 grain.
1 gramme = 15·432349 grains.
1 kilogramme = 15432·349 grains, or 2·20462125 lbs. avoir.

MEASURES INVOLVING REFERENCE TO TWO UNITS.

1 gramme per sq. centimetre = 2·048098 lbs. per sq. foot.
1 kilogramme per sq. metre = ·2048098 " "
1 kilogramme per sq. millimetre = 204809·8 " "
1 kilogrammetre = 7·23314 foot-pounds.

1 force de cheval = 75 kilogrammetres per second, or 542½ foot-pounds per second nearly, whereas 1 horse-power (English) = 550 foot-pounds per second

TABLE FOR THE CONVERSION OF ENGLISH INTO FRENCH MEASURES

MEASURES OF LENGTH.

1 inch = 25·39954 millimetres.
1 foot = ·30479449 metre.
1 yard = ·91438347 metre.
1 mile = 1·60932 kilometre.

MEASURES OF AREA.

1 sq. inch = 645·137 sq. millimetres.
1 sq. foot = ·0928997 sq. metre.
1 sq. yard = ·8360973 sq. metre.
1 sq. mile = 2·589895 sq. kilometres.

SOLID MEASURES.

1 cubic inch = 16386·6 cubic millimetres.
1 cubic foot = ·0283153 cubic metre.
1 cubic yard = ·7645131 cubic metre.

MEASURES OF CAPACITY.

1 pint = ·5676275 litre
1 gallon = 4·54102 litres.
1 bushel = 36·32816 litres.

MEASURES OF WEIGHT.

1 grain = ·064799 gramme.
1 oz. avoir. = 28·3496 grammes.
1 lb. avoir. = ·453593 kilogramme.
1 ton = 1·01605 tonne = 1016·05 kilos.

MEASURES INVOLVING REFERENCE TO TWO UNITS.

1 lb. per sq. foot = 4·88261 kilos. per sq. metre.
1 lb. per sq. inch = ·0703095 kilos. per sq. centimetre.
1 foot-pound = ·138253 kilogrammetre.

HEAT.

CHAPTER XIX.

THERMOMETRY.

175. Heat—Cold.—The words *heat* and *cold* express sensations so well known as to need no explanation; but these sensations are modified by subjective causes, and do not furnish an invariable criterion of objective reality. In fact, we may often see one person suffer from heat while another complains of cold. Even for the same person the sensations of heat and cold are comparative. A temperature of 50° Fahr. suddenly occurring amid the heat of summer produces a very decided sensation of cold, whereas the same temperature in winter has exactly the opposite effect. We may mention an old experiment upon this subject, which is at once simple and instructive. If we plunge one hand into water at 32° Fahr., and the other into water at about 100°; and if after having left them some time in this position we immerse them simultaneously in water at 70°, they will experience very different sensations. The hand which was formerly in the cold water now experiences a sensation of heat; that which was in the hot water experiences a sensation of cold, though both are in the same medium. This plainly shows that the sensations of heat and cold are modified by the condition of the observer, and consequently cannot serve as a sure guide in the study of calorific phenomena. Recourse must therefore be had to some more constant standard of reference, and such a standard is furnished by the thermometer.

176. Temperature.—If several bodies heated to different degrees are placed in presence of each other, an interchange of heat takes place between them, by which they undergo modifications of opposite kinds; those that are hottest grow cooler, and those that are coldest grow warmer; and after a longer or shorter time these inverse phenomena cease to take place, and the bodies come to a state of mutual equilibrium. They are then said to be at the same *temperature.* If a source of heat is now brought to act upon them, their temperature is said to *rise;* if they are left to themselves in a colder medium, they all grow cold, and their temperature is said to *fall.* *Two bodies are said to have the same temperature if when they are placed in contact no heat passes from the one to the other.* If when two bodies are placed in contact heat passes from one to the other, that which gives heat to the other is said to have the higher temperature. Heat always tends to pass from bodies of higher to those of lower temperature.

177. Expansion.—At the same time that bodies undergo these changes in temperature, which may be verified by the different impressions which they make upon our organs, they are subjected to other modifications which admit of direct measurement, and which serve as a means of estimating the changes of temperature themselves. These modifications are of different kinds, and we shall have occasion to speak of them all in the course of this work; but that which is especially used as the basis of thermometric measurement is change of volume. In general, when a body is heated, it increases in volume; and, on the other hand, when it is cooled its volume diminishes. The expansion of bodies under the action of heat may be illustrated by the following experiments.

1. *Solid Bodies.*—We take a ring through which a metal sphere just passes. This latter is heated by holding it over a spirit-lamp, and it is found that after this operation it will no longer pass through the ring. Its volume has increased. If it is now cooled by immersion in water, it resumes its former volume, and will again pass

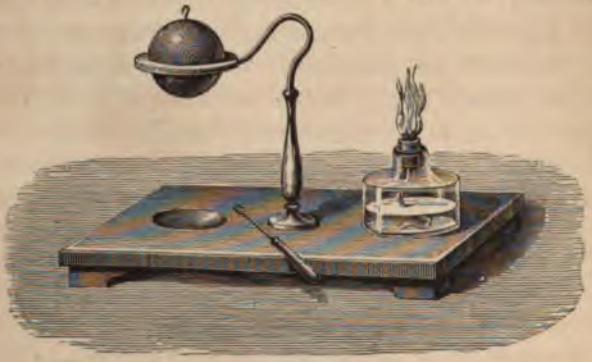


Fig. 182.—Gravesande's Ring.

through the ring. If, while the sphere was hot, we had heated the ring to about the same degree, the ball would still have been able to pass, their relative dimensions being unaltered. This little apparatus is called *Gravesande's Ring*.

2. *Liquids.*—A liquid, as water for instance, is introduced into the apparatus shown in Fig. 183, so as to fill at once the globe and a portion of the tube as far as a. The instrument is then immersed in a vessel containing hot water, and at first the extremity of the liquid column descends for an instant to b; but when the experiment has continued for some time, the liquid rises to a point a' at a considerable height above. This twofold phenomenon is easily explained. The globe, which receives the first impression of heat, increases in volume before any sensible change can take place in the temperature of the liquid. The liquid consequently is unable to fill the entire

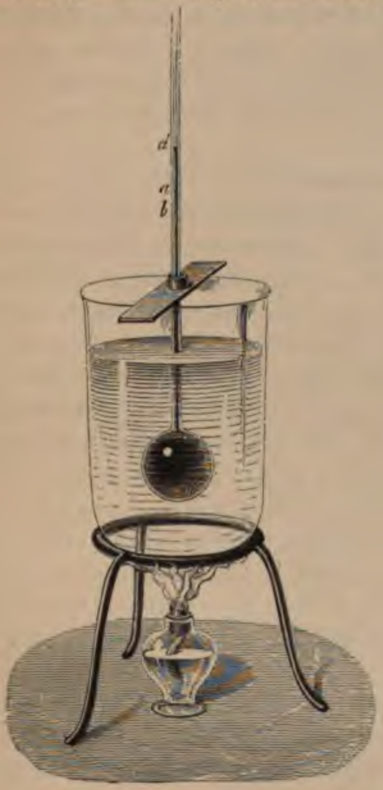


Fig. 183.—Expansion of Liquids.

Fig. 184.—Expansion of Gases.

capacity of the globe and tube up to the original mark, and thus the extremity of the liquid column is seen to fall. But the liquid receiving in its turn the impression of heat, expands also, and as it passes the original mark, we may conclude that it not only expands, but expands more than the vessel which contains it.

3. *Gases.*—The globe in Fig. 184 contains air, which is separated from the external air by a small liquid index. We have only to warm the globe with the hands and the index will be seen to be pushed quickly upwards, thus showing that gases are exceedingly expansible.

178. General Idea of the Thermometer.—Since the volume of a body is always changed by heat, it follows that when a body is subjected to variations of temperature, it undergoes at the same time corresponding variations of volume. If we suppose that the different volumes successively assumed by the body can easily be measured, we may indicate the temperature by stating the volume. And the body will not only indicate its own temperature by this means, it will also exhibit the temperature of the bodies by which it is surrounded, and which are in equilibrium with it as regards temperature; that is, which do not experience those inverse changes mentioned in § 176. Such is the most general idea of the thermometer, which may be defined as *a body which, under the action of heat, exhibits changes of volume which can be ascertained and measured.*

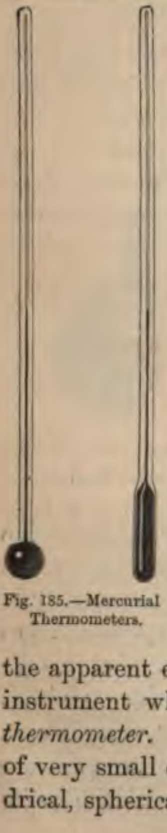


Fig. 185.—Mercurial Thermometers.

179. Choice of the Thermometric Substance.—Any substance whatever will serve as a thermometric substance, and in fact there are several kinds of thermometers, founded upon the expansion of different substances. In order, however, that thermometric indications may be comparable with each other, it is necessary to adopt a standard substance or combination of substances, and physicists have by common consent adopted as the standard of reference the apparent expansion of mercury contained in a glass vessel. The instrument which exhibits this expansion is called the *mercurial thermometer.* It consists essentially, as shown in Fig. 185, of a tube of very small diameter, terminating in a bulb or reservoir of a cylindrical, spherical, or any other form. The reservoir and a portion of the tube are filled with mercury. If the temperature varies, the level of the liquid will rise or fall in the tube, and the points at which it remains stationary can be easily identified by means of a scale attached to or engraved on the tube.

The choice of mercury as a thermometric substance is extremely suitable. It is a liquid which may easily be procured in a state of purity. It is a very good conductor of heat, and consequently soon comes into equilibrium of temperature with the bodies which it touches. Besides, its *calorific capacity* is very small, so that if it be brought into contact with a heated body, for instance, at whose expense it grows hot, this body experiences in consequence only a very slight change of temperature, which may generally be neglected.

180. Construction of the Mercurial Thermometer.—The construction of a mercurial thermometer is an operation of great delicacy, and comprises several different processes, which we shall successively indicate.

1. *Choice of the Tube.*—The first object is to procure a tube of as uniform bore as possible. In order to ascertain whether this condition is fulfilled, a small column of mercury is introduced into the tube, and its length in different parts of the tube is measured. If these lengths are exactly equal, the tube must be of uniform bore. This is not generally the case, and we have to content ourselves with an approximation to this result; but we must reject tubes in which the differences of length observed are too great. When a suitable tube has been obtained, a reservoir is either blown at one end or attached by melting, the former plan being usually preferable.

When a thermometer of great precision is required, the tube is first *calibrated;* that is, divided into parts of equal volume.

2. *Introduction of the Mercury.*—At the upper extremity of the tube a bulb has been blown, drawn out to a point, at which there is a small opening; this bulb is gently heated, and the point is then immersed in a vessel containing mercury (Fig. 186). The air in the tube growing cold, suffers a diminution at once of volume and of pressure, so that mercury is forced into the bulb by the atmospheric pressure. The end of the point is then closed to prevent the escape of mercurial vapours, and the reservoir and tube, still remaining empty, are heated in a gas or charcoal furnace (Fig. 187), so as to rarefy the contained air. The liquid in the bulb is then heated, and on setting the instrument upright, and allowing it to cool, a portion of the mercury enters the reservoir in consequence of the contraction

of the air. The liquid in the reservoir is then heated to ebullition, the air is expelled from the reservoir and tube by the vapour of mercury, and on placing the instrument in an upright position, the mercury during the process of cooling enters the reservoir and completely fills it. If a bubble of air still remains, as is often the case, it may be expelled by repeating the same operation several times. The quantity of mercury to be left is then regulated according to the temperatures which the instrument is intended to indicate; the bulb at the upper end is removed, and the tube, having been drawn out to a point, is hermetically sealed at the moment when the mercury reaches its extremity, so as to leave no air in the interior.

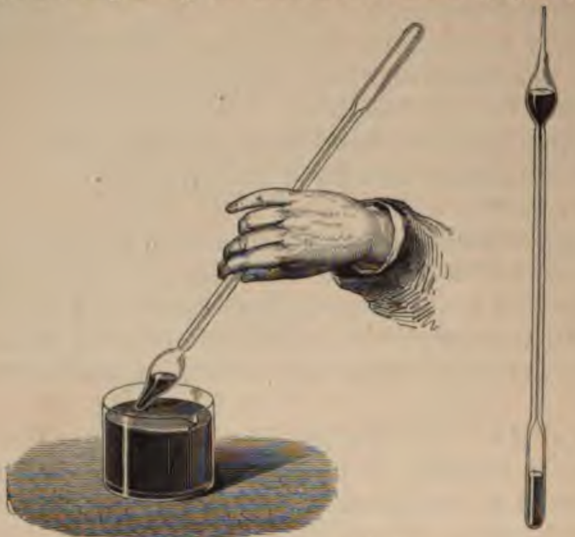


Fig. 186.—Introduction of the Mercury.

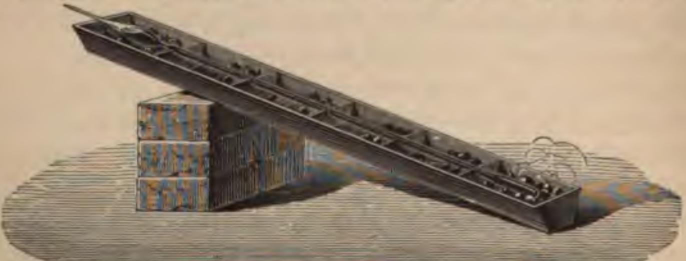


Fig. 187.—Furnace for heating Thermometers.

3. *Determination of the Fixed Points.*—The instrument, under these conditions, and with any scale of equal parts marked on the tube, would of course indicate variations of temperature, but these indications would be arbitrary, and two thermometers so constructed would in general give different indications.

In order to insure that the indications of different thermometers shall be comparable, it has been agreed to adopt two standard temperatures, which can easily be reproduced and maintained for a considerable time, and to denote them by fixed numbers. These two temperatures are the freezing-point and boiling-point of water; or to speak more strictly, the temperature of melting ice, and the temperature of the steam given off by water boiling under average atmospheric pressure. It has been observed that if the thermometer be surrounded with melting ice (or melting snow), the mercury, under whatever circumstances the experiment is performed, invariably stops at the same point, and remains stationary there as long as the melting continues. This then is a fixed temperature. On the Centigrade scale it is called zero, on Fahrenheit's scale 32°.

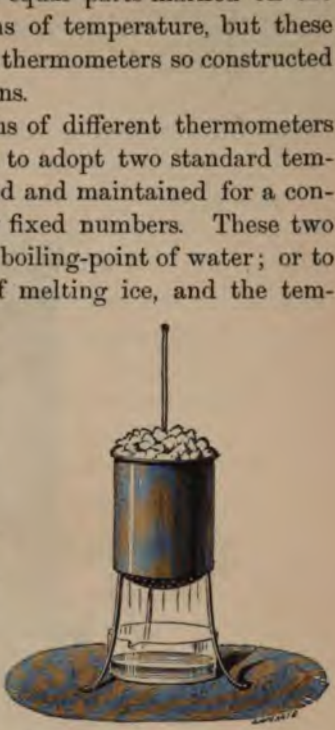


Fig. 188.—Determination of Freezing-point.

In order to mark this point on a thermometer, it is surrounded by melting ice, which is contained in a perforated vessel, so as to allow the water produced by melting to escape. When the level of the mercury ceases to vary, a mark is made on the tube with a fine diamond at the extremity of the mercurial column. This is frequently called for brevity the *freezing-point.*

It has also been observed that if water be made to boil in an open metallic vessel, under average atmospheric pressure (760 millimetres, or 29·922 inches), and if the thermometer be plunged into the steam, the mercury stands at the same point during the entire time of ebullition, provided that the external pressure does not change. This second fixed temperature is called 100° in the Centigrade scale (whence the name), and 212° on Fahrenheit's scale. In order to mark this second point on the thermometer, an appar[illegible] employed which was devised by Gay-Lussac, and perfected [illegible]ault. It consists of a copper boiler (Fig. 189) containing water which is raised to ebullition by means of a furnace. The steam circulates through a double casing, and escapes by a tube near the bottom. The thermometer is fixed in the interior casing, and when the mercury has

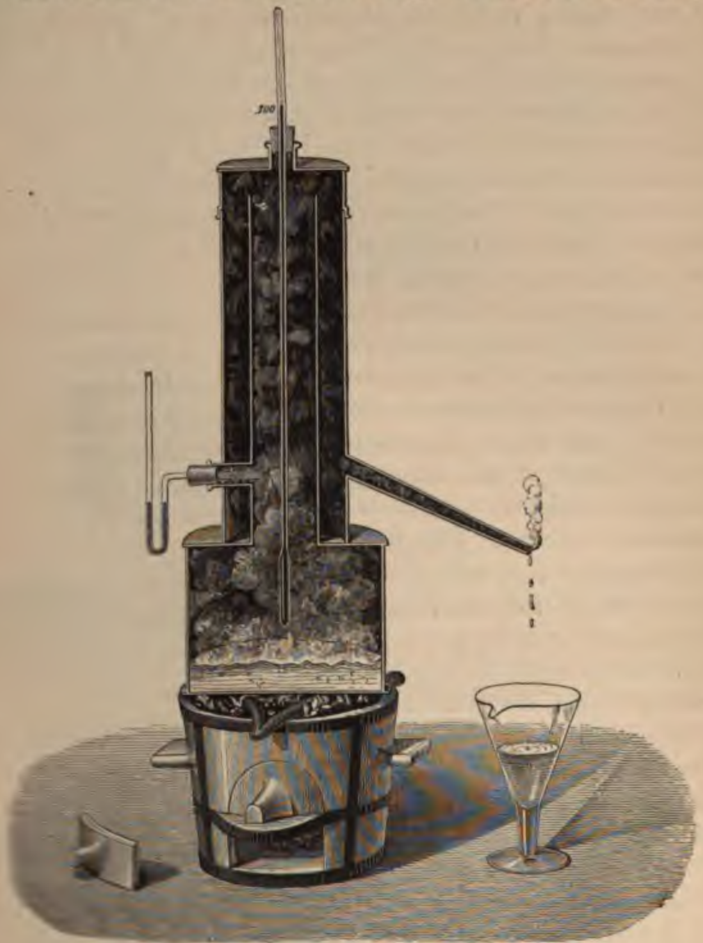


Fig. 189.—Determination of Boiling-point.

become stationary, a mark is made at the point at which it stops, which denotes what is commonly called for brevity the *boiling-point.* It now only remains to divide the portion of the instrument between the freezing and boiling points into equal parts corresponding to single degrees, and to continue the division beyond the fixed points. Below the zero point are marked the numbers 1, 2, 3, &c. These temperatures are generally expressed with the sign —. Thus the temperature of 17° below zero is written —17°.

A small manometric tube, open at both ends, serves to show, by the equality of level of the mercury in its two branches, that the ebullition is taking place at a pressure equal to that which prevails externally, and consequently that the steam is escaping with sufficient freedom. It frequently happens that the external pressure is not exactly 760 millimetres, in which case the boiling-point should be placed a little above or a little below the point at which the mercury remains stationary, according as the pressure is less or greater than this standard pressure. When the difference on either side is inconsiderable, the position of the boiling-point is calculated by the rule, that a difference of 20·6 millimetres, either above or below the normal pressure, causes a difference of 1° in the temperature of the steam produced. We shall return to this point in Chap. xxvi.

181. Adjustment of the Quantity of Mercury.—In order to avoid complicating the above explanation, we have omitted to consider an operation of great importance, which should precede those which we have just described. This is the determination of the volume which must be given to the reservoir, in order that the instrument may have the required range. When the reservoir is cylindrical, this is very easily effected in the following manner. Suppose we wish the thermometer to indicate temperatures comprised between —20° and 130° Cent., so that the range is to be 150°; the reservoir is left open at O (Fig. 190), and is filled through this opening, which is then hermetically sealed. The instrument is then immersed in two baths whose temperatures differ by 50°, for instance, and the mercury rises through a distance *mm'*. This length, if the quantity of mercury in the reservoir be exactly sufficient, should be the third part of the length of the stem. But the quantity of mercury in the reservoir is always taken too large at first, so that it has only to be reduced, and thus the space traversed by the liquid is at first too great. Suppose it to be equal to $\frac{3}{4}$ths of the length of the stem. The degrees will then be too long, in the ratio $\frac{3}{4} : \frac{1}{3} = \frac{9}{4}$. That is, the reservoir is $\frac{9}{4}$ of what it should be. We therefore measure off $\frac{4}{9}$ths of the length of the reservoir, beginning at the end next the stem; this distance is marked by a line, and the end O is then broken and the mercury suffered to escape. The glass

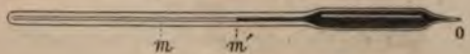


Fig. 190.

is then melted down to the marked line, and the reservoir is thus brought to the proper dimensions. It only remains to regulate the quantity of mercury admitted, by making it fill the tube at the highest temperature which the instrument is intended to indicate.

If the reservoir were spherical, which is a shape generally ill adapted for delicate thermometers, the foregoing process would be inapplicable, and it would be necessary to determine the proper size by trial.

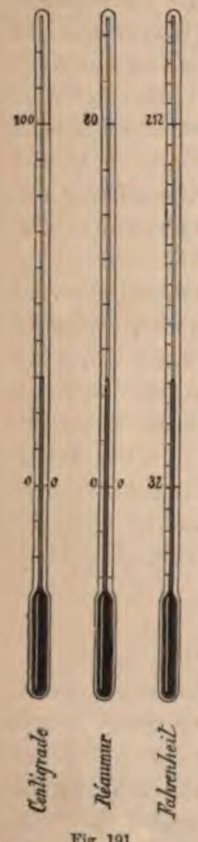


Fig. 191.
Thermometric Scales.

182. Thermometric Scales.—In the *Centigrade* scale the freezing-point is marked 0°, and the boiling-point 100°. In *Réaumur's* scale, which is still sometimes used abroad, the freezing-point is also marked 0°, but the boiling-point is marked 80°. Hence, 5 degrees on the former scale are equal to 4 on the latter, and the reduction of temperatures from one of these scales to the other can be effected by multiplying by $\frac{4}{5}$ or $\frac{5}{4}$.

For example, the temperature 75° Centigrade is the same as 60° Réaumur, since $75 \times \frac{4}{5} = 60$; and the temperature 36° Réaumur is the same as 45° Centigrade, since $36 \times \frac{5}{4} = 45$.

The relation between either of these scales and that of *Fahrenheit* is rather more complicated, inasmuch as Fahrenheit's zero is not at freezing-point, but at 32 of his degrees below it.

As regards intervals of temperature, 180 degrees Fahrenheit are equal to 100 Centigrade, or to 80 Réaumur, and hence, in lower terms, 9 degrees Fahrenheit are equal to 5 Centigrade, or to 4 Réaumur.

The conversion of temperatures themselves (as distinguished from intervals of temperature) will be best explained by a few examples.

Example 1. To find what temperatures on the other two scales are equivalent to the temperature 50° Fahrenheit.

Subtracting 32, we see that this temperature is 18 Fahrenheit degrees above freezing-point, and as this interval is equivalent to $18 \times \frac{5}{9}$, that is 10 Centigrade degrees, or to $18 \times \frac{4}{9}$, that is 8 Réaumur degrees, the equivalent temperatures are respectively 10° Centigrade and 8° Réaumur.

Example 2. To find the degree on Fahrenheit's scale, which is equivalent to the temperature 25° Centigrade.

An interval of 25 Centigrade degrees is equal to $25 \times \frac{9}{5}$, that is 45 Fahrenheit degrees, and the temperature in question is above freezing-point by this amount. The number denoting it on Fahrenheit's scale is therefore $32 + 45$, that is 77°.

The rules for the conversion of the three thermometric scales may be summed up in the following formulæ, in which F, C, and R denote equivalent temperatures expressed in degrees of the three scales:—

$$\mathrm{F} = \tfrac{9}{5}\mathrm{C} + 32 = \tfrac{9}{4}\mathrm{R} + 32.$$
$$\mathrm{C} = \tfrac{5}{4}\mathrm{R} = \tfrac{5}{9}(\mathrm{F} - 32).$$
$$\mathrm{R} = \tfrac{4}{5}\mathrm{C} = \tfrac{4}{9}(\mathrm{F} - 32).$$

It is usual in stating temperatures to indicate the scale referred to by the abbreviations *Fahr.*, *Cent.*, *Réau.*, or more briefly by the initial letters F., C., R.

183. Apparent Expansion of Mercury. Degree of the Mercurial Thermometer.—The indications of the mercurial thermometer depend not upon the real but upon the *apparent* expansion of mercury, that is, upon the difference between the expansion of the mercury and that of the glass in which it is contained.

To understand the physical meaning of a degree, suppose that we have a thermometric tube (Fig. 192) divided into parts of equal capacity, and that by gauging the reservoir we have ascertained its capacity to be equal to N of these parts. Mercury is introduced, and when the instrument is surrounded with melting ice the mercury fills the bulb and n parts of the tube. The instrument is then raised to the temperature of 100° C., and the mercury expands so as to occupy n' parts of the stem. The apparent volumes of the mercury at 0° and 100° Centigrade are therefore $\mathrm{N} + n$ and $\mathrm{N} + n'$ respectively, and the apparent increase of volume is $n' - n$. The apparent increase per unit volume is therefore $\frac{n'-n}{\mathrm{N}+n}$, and as this is the increase for 100° the apparent expansion per degree Centigrade is $\frac{1}{100}\,\frac{n'-n}{\mathrm{N}+n}$. This quantity is found by experiment to be about equal to $\frac{1}{6480}$. Each degree Centigrade represents then a difference of apparent volume of the mercury equal to about $\frac{1}{6480}$ of its volume at freezing-point.

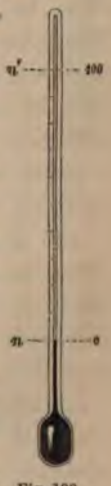


Fig. 192.

184. Comparability of Mercurial Thermometers.—This enables us to examine the important question, whether different thermometers are comparable with each other, that is, whether they will indicate the same temperature under the same conditions. This must evidently be the case where the glass employed for the construction of the tubes is absolutely the same. The agreement will likewise be exact, even when the apparent expansions due to the quality of the glass employed in each case are not the same, provided that they preserve a constant ratio at different temperatures.

Experiment alone can teach us whether this disagreement actually exists, and in what degree. The result of Regnault's investigations upon this point tends to show that up to 300° Cent. this disagreement is almost nothing, or, at any rate, may be neglected with perfect safety; above this point a slight difference is observed, which increases to about 3° or 4° at the temperature of 350°, that is, at the superior limit to the use of the mercurial thermometer.

This defect in the comparability of thermometers, slight as it is, must be attributed to irregularities in the expansion of the glass. The influence of these irregularities would obviously be less sensible with a more expansible material than mercury, and this is the reason that in experiments where great precision is necessary air-thermometers are employed, which at the same time serve to indicate the highest temperatures, whereas mercury cannot be employed beyond 350°, its boiling-point.

185. Displacement of the Zero Point.—A thermometer left to itself after being made, gradually undergoes a contraction of its capacity, leading to a uniform error of excess in its indications. This phenomenon is attributable to molecular change in the glass, which has, so to speak, been tempered in the construction of the instrument, and to atmospheric pressure on the exterior of the bulb, which is unresisted by the internal vacuum. The progress of this change ceases at the end of a certain time, about fifteen or eighteen months, and the displacement is always inconsiderable, never amounting to a degree. In precise experiments, however, it is necessary to verify the position of the zero point in the thermometer employed, and, in the observation of temperatures, to take into consideration the slight displacement which may have occurred.

186. Sensibility of the Thermometer.—The power of the instrument to detect very small differences of temperature may be regarded as measured by the length of the degrees, which is proportional to the capacity of the bulb directly and to the section of the tube inversely. In fact, if l denote the length of one degree, and s the sectional area of the tube, ls will be the volume of one degree, which is $\frac{1}{6480}C$, where C denotes the capacity of the bulb, together with as much of the tube as is below the freezing-point. Hence, $l=\frac{1}{6480}\frac{C}{s}$, which varies directly as C, and inversely as s.

Quickness of action, on the other hand, requires that the bulb be small in at least one of its dimensions, so that no part of the mercury shall be far removed from the exterior, and also that the glass of the bulb be thin.

Quickness of action is important in measuring temperatures which vary rapidly. It should also be observed that, as the thermometer, in coming to the temperature of any body, necessarily causes an inverse change in the temperature of that body, it follows that when the mass of the body to be investigated is very small, the thermometer itself should be of extremely small dimensions, in order that it may not cause a sensible variation in the temperature to be ascertained.

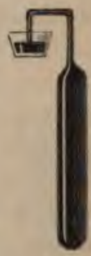


Fig. 193. Weight Thermometer.

187. Weight Thermometer.—In this thermometer, which often takes the place of the ordinary thermometer in physical investigations, the stem is done away with, and the mercury contained in the reservoir overflows into a small cup, where it is collected; and the temperature is deduced from the weight of the mercury which thus escapes. Let P be the weight of the mercury which fills the reservoir at freezing-point, and π the weight which issues when the instrument is placed in the steamer in order to determine the boiling-point. The apparent expansion between these points is evidently represented by the fraction $\frac{\pi}{P-\pi}$, and, consequently, the value of a degree Centigrade is the one-hundredth part of this fraction, that is $\frac{\pi}{100\,(P-\pi)}$. Suppose now that the instrument, containing again a weight P of mercury at zero is placed in a bath whose temperature we wish to determine, and that a weight p of mercury flows over. The whole apparent expansion is $\frac{p}{P-p}$, and dividing this by the value of a degree, we obtain the temperature required, which is thus expressed by the formula

$$T=\frac{p}{P-p}\div\frac{\pi}{100\,(P-\pi)}=100\,\frac{p}{\pi}\cdot\frac{P-\pi}{P-p}.$$

188. Alcohol Thermometer.—In the construction of thermometers other liquids may be introduced instead of mercury, and alcohol is very frequently employed for this purpose. But if an alcohol thermometer were constructed so as to agree with a mercurial thermometer at two fixed temperatures, and were graduated by dividing the intervening space into equal parts, and continuing the equal graduations both ways, it would be found to give different readings from a mercurial thermometer, except at or very near the two fixed temperatures. This fact may be expressed by saying, that alcohol does not expand equally for equal increments of temperature as indicated by a mercurial thermometer; or, more symmetrically, by saying that intervals of temperature which are equal as measured by the expansion of mercury, are not equal as measured by the expansion of alcohol.

In practice, alcohol thermometers are graduated by comparison with mercurial thermometers, and the degrees of an alcohol thermometer have consequently unequal volumes in different parts of the scale. The degrees, in fact, increase in length as we ascend on the scale.

Alcohol has the disadvantage of being slower in its action than mercury, on account of its inferior conductivity; but it can be employed for lower temperatures than mercury, as the latter congeals at —39° Cent. (—38° Fahr.), whereas the former has never congealed at any temperature yet attained.

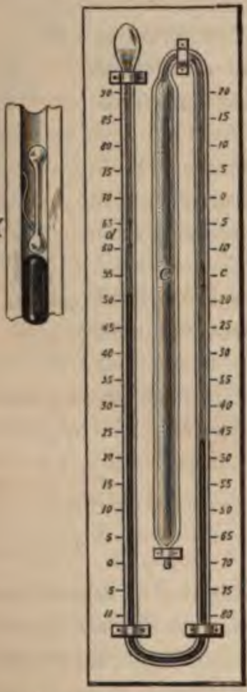


Fig. 194A.—Six's Self-registering Thermometer.

189. Self-registering Thermometers.—It is often important for meteorological purposes to have the means of knowing the highest or the lowest temperature that occurs during a given interval. Instruments intended for this purpose are called maximum and minimum thermometers.

The oldest instrument of this class is *Six's* (Fig. 194A), which is at once a maximum and a minimum thermometer. It has a large cylindrical bulb C filled with alcohol, which also occupies a portion of the tube. The remainder of the tube is partly filled with mercury, which occupies a portion of the tube shaped like the letter U, one extremity of the mercurial column being in contact with the alcohol already mentioned, while the other extremity is in contact with a second column of alcohol; and beyond this there is a small space occupied only with air, so as to leave room for the expansion of the liquids. When the alcohol in the bulb expands it pushes the mercurial column before it, and when it contracts the mercurial column follows it. The extreme points reached by the two ends of the mercurial column are registered by a pair of light steel indices *c*, *d* (shown on an enlarged scale at K), which are pushed before the ends of the column, and then are held in their places by springs, which are just strong enough to prevent slipping, so that the indices do not follow the mercury in its retreat. One of the indices *d* registers the maximum and the other *c* the minimum temperature which has occurred since the instrument was last set. The setting consists in bringing the indices into contact with the ends of the mercurial column, and is usually effected by means of a magnet. This instrument is now, on account of its complexity, little used. It possesses, however, the advantages of being equally quick (or slow) in its action for maximum and minimum temperatures, which is an important property when these temperatures are made the foundation for the computation of the mean temperature of the interval, and of being better able than most of the self-registering thermometers to bear slight jolts without disturbance of the indices.

Rutherford's self-registering thermometers are frequently mounted together on one frame, as in Fig. 195, but are nevertheless distinct instruments. His *minimum* thermometer, which is the only minimum thermometer in general use, has alcohol for its fluid, and is always placed with its tube horizontal, or nearly so. In the fluid column there is a small index *n* of glass or enamel, shaped like a dumb-bell.

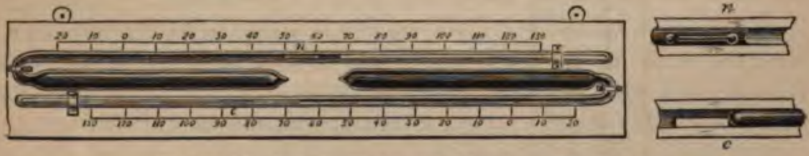


Fig. 195.—Rutherford's Maximum and Minimum Thermometers.

When contraction occurs, the index, being wetted by the liquid, is forced backwards by the contractile force of the superficial film which forms the extremity of the liquid column (§ 97); but when expansion takes place the index remains stationary in the interior of the liquid. Hence the minimum temperature is indicated by the position of the forward end of the index. The instrument is set by inclining it so as to let the index slide down to the end of the liquid column.

The only way in which this instrument is liable to derangement, is by a portion of the spirit evaporating from the column and becoming condensed in the end of the tube, which usually terminates in a small bulb. When the portion thus detached is large, or when the column of spirit becomes broken into detached portions by rough usage in travelling, "let the thermometer be taken in the hand by the end farthest from the bulb, raised above the head, and then forcibly swung down towards the feet; the object being, on the principle of centrifugal force, to send down the detached portion of spirit till it unites with the column. A few throws or swinging strokes will generally be sufficient; after which the thermometer should be placed in a slanting position, to allow the rest of the spirit still adhering to the sides of the tube to drain down to the column. But another method must be adopted if the portion of spirit in the top of the tube be small. Heat should then be applied slowly and cautiously to the end of the tube where the detached portion of spirit is lodged; this being turned into vapour by the heat will condense on the surface of the unbroken column of spirit. Care should be taken that the heat is not too quickly applied. . . . The best and safest way to apply the requisite amount of heat, is to bring the end of the tube slowly down towards a minute flame from a gas-burner; or if gas is not to be had, a piece of heated metal will serve instead."[1]

Rutherford's *maximum* thermometer is a mercurial thermometer, with the stem placed horizontally, and with a steel index *c* in the tube outside the mercurial column. When expansion occurs, the index, not being wetted by the liquid, is forced forwards by the contractile force of the superficial film which forms the extremity of the liquid column (§ 97); but when contraction takes place, the index remains stationary outside the liquid. Hence the maximum temperature is indicated by the position of the backward end of the index. The instrument is set by bringing the index into contact with the end of the liquid column, an operation which is usually effected by means of a magnet.

This thermometer is liable to get out of order after a few years' use, by chemical action upon the surface of the index, which causes it to become wetted by the mercury, and thus renders the instrument useless.

---

[1] Buchan's *Handy Book of Meteorology*, p. 62.

Phillips' maximum thermometer (invented by Professor Phillips, the eminent geologist, and made by Casella) is recommended for use in the official *Instructions for Taking Meteorological Observations*, drawn up by Sir Henry James for the use of the Royal Engineers. It is a mercurial thermometer not deprived of air. It has an exceedingly fine bore, and the mercurial column is broken by the insertion of a small portion of air. The instrument is set by reducing this portion of air to the smallest dimensions which it can be made to assume, and is placed in a horizontal position. When the mercury expands it pushes forwards this intervening air and the detached column of mercury beyond it; but when contraction takes place the intervening air expands, and the detached column remains unmoved.

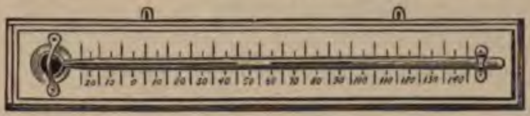


Fig. 194 B.—Phillips' Maximum Thermometer.

"The thread of mercury in these thermometers is easily broken at any point required, by simply raising the bulb end, and allowing the mercury to run into the open cell at the end; and, as it descends, detaching, with a slight jerk, as much of it as may be thought necessary, which should be an inch, or an inch and a half."[1]

The detached column is not easily shaken out of its place, and when the bore of the tube is made sufficiently narrow the instrument may even be used in a vertical position, a property which is often of great service.

In Negretti and Zambra's maximum thermometer (Fig. 194), which is employed at the Royal Observatory, Greenwich, there is an obstruction in the bent part of the tube, near the bulb, which barely leaves room for the mercury to pass when forced up by

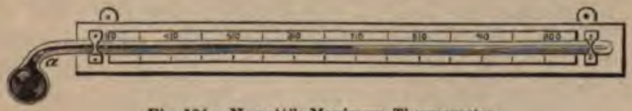


Fig. 194.—Negretti's Maximum Thermometer.

---

[1] *Instructions for Taking Meteorological Observations.* By Colonel Sir Henry James, R.E., Director of the Ordnance Survey.

expansion, and is sufficient to prevent it from returning when the bulb cools.

The objection chiefly urged against this thermometer is the extreme mobility of the detached column, which renders it very liable to accidental displacement; but in the hands of a skilful observer this is of no moment. Dr. Balfour Stewart (*Elementary Treatise on Heat*, p. 20, 21), says:—"When used, the stem of this instrument ought to be inclined downwards. . . . It does not matter if the column past the obstruction go down to the bottom of the tube; for when the instrument is read, it is gently tilted up until this detached column flows back to the obstruction, where it is arrested, and the end of the column will then denote the maximum temperature. In resetting the instrument, it is necessary to shake the detached column past the obstruction in order to fill up the vacancy left by the contraction of the fluid after the maximum had been reached."

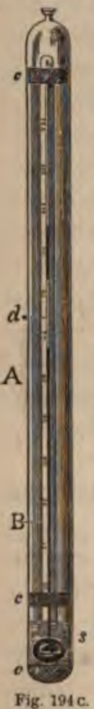


Fig. 194c. Thomson's Protected Thermometer.

MERCURIAL MINIMUM THERMOMETERS.—As it is obviously undesirable that the minimum thermometer employed should be slower in its action than the maximum thermometer used in conjunction with it, several attempts have been made to construct a minimum thermometer in which mercury instead of alcohol shall be the expanding fluid (see a description of Casella's mercurial minimum thermometer, Stewart on *Heat*, p. 22); but no one has yet succeeded in producing such an instrument fit for general use.

DEEP-SEA AND WELL THERMOMETERS.—The instruments which have been most successfully employed for the observation of the temperature of water at great depths are self-registering thermometers either of Six's or Phillips' construction, inclosed in a glass-case, hermetically sealed, containing air and a little alcohol. The glass-case and inclosed air protect the bulb of the thermometer from the immense pressure of the superincumbent water, which by compressing the bulb would force mercury into the tube, and make the reading too high. The instrument represented in Fig. 194c was designed by Sir Wm. Thomson, and is used by the Committee on Underground Temperature appointed by the British Association. A is the protecting case, B the Phillips' thermometer inclosed in it, and supported by three pieces of cork *ccc*. A small quantity of spirit *s* occupies the lower part of the case; *d* is the air-bubble characteristic of Phillips' thermometer, and serving to separate one portion of the mercurial column from the rest. In the figure this air-bubble is represented as expanded by the descent of the lower portion of mercury, while the upper portion remains suspended by adhesion. This instrument has been found to register correctly even under a pressure of 2½ tons to the square inch.

The use of the spirit *s* is to bring the bulb more quickly to the temperature of the surrounding medium.

Another instrument, designed, like the foregoing, for observations in wells and borings, is *Walferdin's maximum thermometer* (Fig. 196). Its tube terminates above in a fine point opening into a cavity of considerable size, which contains a sufficient quantity of mercury to cover the point when the instrument is inverted. The instrument is set by placing it in this inverted position and warming the bulb until the mercury in the stem reaches the point and becomes connected with the mercury in the cavity. The bulb is then cooled to a temperature lower than that which is to be observed, and during the operation of cooling mercury enters the tube so as always to keep it full. The instrument is then lowered in the erect position into the bore where observations are to be made, and when the temperature of the mercury rises a portion of it overflows from the tube. To ascertain the maximum temperature which has been experienced, the instrument may be immersed in a bath of known temperature, less than that of the boring, and the amount of void space in the upper part of the tube will indicate the excess of the maximum temperature experienced above that of the bath.

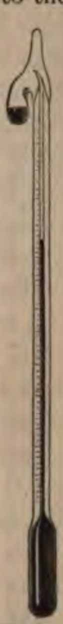


Fig. 196.

If the tube is not graduated, the maximum temperature can be ascertained by gradually raising the temperature of the bath till the tube is just full.

If the tube is graduated, the graduations can in strictness only indicate true degrees for some one standard temperature of setting, since the length of a true degree is proportional to the quantity of mercury in the bulb and tube; but a difference of a few degrees in the temperature of setting is immaterial, since 10° Cent. would only alter the length of a degree by about one six-hundredth part.

190. Thermograph.—A much more complete method of obtaining a register of the indications of a thermometer in the absence of an observer is now adopted in the principal British observatories. It consists in the photographic registration of the height of the mercurial column at every instant during the entire day. A sheet of sensitized paper is mounted on a vertical cylinder just behind the mercurial column, which is also vertical, and is protected from the action of light by a cover of blackened zinc, with the exception of a narrow vertical strip just behind the mercurial column. A strong beam of light from a lamp or gas flame is concentrated by a cylindric lens, so that if the thermometer were empty of mercury a bright vertical line of light would be thrown on the paper. As this beam of light is intercepted by the mercury in the tube, which for this purpose is made broad and flat, only the portion of the paper above the top of the mercurial column receives the light, and is photographically affected. The cylinder is made to revolve slowly by clock-work, and if the mercury stood always at the same height, the boundary between the discoloured and the unaffected parts of the paper would be straight and horizontal, in consequence of the horizontal motion of the paper itself. In reality, the rising and falling of the mercury, combined with the horizontal motion of the paper, causes the line of separation to be curved or wavy, and the height of the curve above a certain datum-line is a measure of the temperature at each instant of the day.[1] The whole apparatus is called a *thermograph*, and apparatus of a similar character is employed for obtaining a continuous photographic record of the indications of the barometer[2] and magnetic instruments.

191. Metallic Thermometers.—Thermometers have sometimes been constructed of solid metals. Breguet's thermometer, for example (Fig. 197), consists of a helix carrying at its lower end a horizontal needle which traverses a dial. The helix is composed of three metallic strips, of silver, gold, and platinum, soldered together so as to form a single ribbon. The silver, which is the most expansible, is placed in the interior of the helix; the platinum, which is the least expansible, on the exterior; and the gold serves to connect them. When the temperature rises, the helix unwinds and produces a deflection of the needle; when the temperature falls, the helix winds up and deflects the needle in the opposite direction.

---

[1] Strictly speaking, the temperatures corresponding to the various points of the curve are not read off by reference to a single datum-line, but to a number of datum-lines which represent the shadows of a set of horizontal wires stretched across the tube of the thermometer at each degree, a broader wire being placed at the decades, and also at 32°, 52°, and 72°.

In order to give long degrees, the bulb of the thermometer is made very large—eight inches long, and ·4 of an inch in internal diameter.—(*Greenwich Observations*, 1847.)

[2] See § 110A.

Fig. 198 represents another dial-thermometer, in which the thermometric portion is a double strip composed of steel and brass, bent into a circular form. One extremity is fixed, the other is jointed to the shorter arm of a lever, whose longer arm carries a toothed sector. This latter works into a pinion, to which the needle is attached.

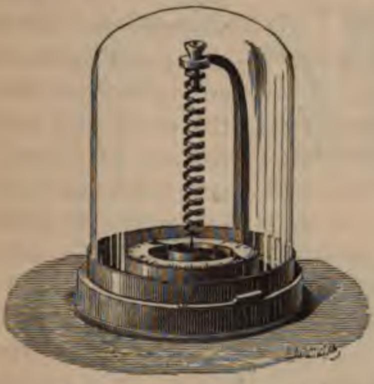


Fig. 197.—Breguet's Thermometer.

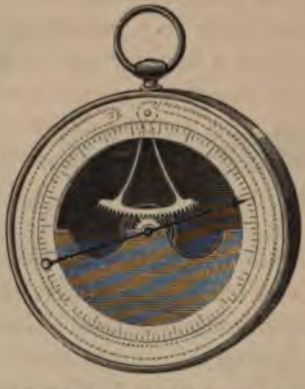


Fig. 198.—Metallic Thermometer.

It may be remarked that dial-thermometers are very well adapted for indicating maximum and minimum temperatures, it being only necessary to place on opposite sides of the needle a pair of movable indices, which could be pushed in either direction according to the variations of temperature.

Generally speaking, metallic thermometers offer great facilities for automatic registration.

In Secchi's meteorograph, for example, the temperature is indicated and registered by the expansion of a long strip of brass (about 17 metres long) kept constantly stretched by a suitable weight; this expansion is rendered sensible by a system of levers connected with the tracing point. The thermograph of Hasler and Escher consists of a steel and a brass band connected together and rolled into the form of a spiral. The movable extremity of the spiral, by acting upon a projecting arm, produces rotation of a steel axis which carries the tracer.

192. Pyrometers.—Metallic thermometers can generally be employed for measuring higher temperatures than a mercurial thermometer could bear; but there is great difficulty in constructing any instrument to measure temperatures as high as those of furnaces. Instruments intended for this purpose are called pyrometers.

Wedgwood, the famous potter, invented an apparatus of this kind, consisting of a gauge for measuring the contraction experienced by a piece of baked clay when placed in a furnace; and Brongniart introduced into the porcelain manufactory at Sèvres the instrument represented in Fig. 199, consisting of an iron bar lying in a groove in a porcelain slab, with one end abutting against the bottom of the groove, and the other projecting through the side of the furnace, where it gave motion to an indicator.

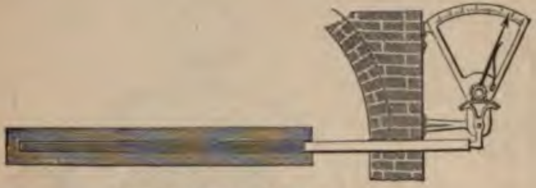


Fig. 199.—Brongniart's Pyrometer.

Neither of these instruments has, however, been found to furnish consistent indications, and the only instrument that is now relied on for the measurement of very high temperatures is the air-thermometer.

193. Differential Thermometer.—Leslie of Edinburgh invented, in the beginning of the present century, an ingenious instrument which enables us to measure small variations of temperature. A column of sulphuric acid, coloured red, stands in the two branches of a bent tube, the extremities of which terminate in two globes of equal volume (Fig. 200).

When the air contained in the two globes is at the same temperature, whatever that temperature may be, the liquid, if the instrument is in order, stands at the same height in the two branches. This point is marked zero. One of the globes being then maintained at a constant temperature, the other is raised through, for instance, 5 degrees, when the column rises on the side of the colder globe up to a point *a*, and descends on the other side to a point *b*. Suppose the space traversed by the liquid in each branch to be divided into 10 equal parts, each part will be equivalent to a quarter of a degree.

This division is continued upon each branch on both sides of zero.

The differential thermometer is an instrument of great sensibility, and enabled Leslie to make some very delicate investigations on the subject of the radiation of heat. It is now, however, superseded by the thermo-pile invented by Melloni. This latter instrument will be described in another portion of this work. Rumford's thermoscope (Fig. 201) is analogous to Leslie's differential thermometer. It differs from it in having the horizontal part much longer, and the vertical branches shorter. In the horizontal tube is an alcohol index, which, when the two globes are at the same temperature, occupies exactly the middle.

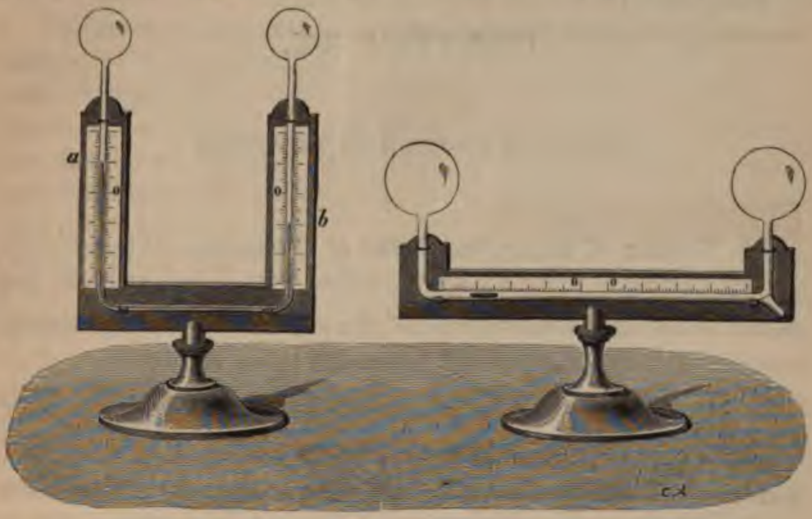


Fig. 200.—Leslie's Differential Thermometer.

Fig. 201.—Rumford's Thermoscope

The tube is divided into equal parts, and the number of divisions traversed by the index is proportional very nearly to the difference of temperature between the two bulbs.

CHAPTER XX.

FORMULÆ RELATING TO EXPANSION.

194. Measure of Expansion, Factor of Expansion.—When a substance expands, so that its volume changes from V to $V'=V+v$, the ratio ^{v} is the numerical measure of the expansion per unit volume, and is usually called simply the expansion of the substance.

Another ratio which it is frequently necessary to consider, is $\frac{V'}{V}$, or $1+\frac{v}{V}$, that is to say, the ratio of the final to the initial volume. This may conveniently be called the *factor of expansion*, or the *expansion factor*. If m denote the expansion, $1+m$ will be the factor of expansion, and we have

$$V'=V\,(1+m). \qquad (1)$$

195. Coefficient of Expansion.—It often happens that when the temperature of a body is increased by successive equal amounts, the successive increments of volume are also equal. In this case the body is said to expand uniformly between the extreme temperatures, and if V denote the volume of the body at 0° Cent., and V' its volume at $t°$, then we have

$$V'=V\,(1+K\,t); \qquad (2)$$

where K is a constant number, called the coefficient of expansion per degree Centigrade.

The coefficient of expansion per degree Fahrenheit will be $\frac{5}{9}$ of this value of K, and the coefficient of expansion for the interval from 0° to 100° C. (if the expansion be uniform through this range) will be 100 K.

196. It is usual to employ the name *coefficient of expansion* to denote the coefficient of expansion per degree, the thermometric scale referred to being stated in the context.

Example. The volume of a glass vessel is 450 cubic inches at 0° C.; find its volume at 80° C., the coefficient of expansion for glass being ·00002. By (1) we have

$$V' = 450\ (1 + 80 \times \cdot 00002) = 450 \cdot 72 \text{ cubic inches.}$$

197. Cubic, Linear, and Superficial Expansion.—Thus far we have considered only expansion of volume. When a solid body expands, we may consider separately the increase of one of the linear dimensions of the body; this is called the *linear expansion.* Or we may consider the increase in area of any portion of its surface, which is called the *superficial expansion;* or finally, the increase of volume, which is called expansion of volume, or *cubical expansion.* By substituting the words "length" and "surface" for "volume" in § 194 we obtain definitions of linear and superficial expansion as numerically expressed, and we can demonstrate the two following propositions:—

(1.) The cubical expansion is three times the linear expansion.

(2.) The superficial expansion is twice the linear expansion.

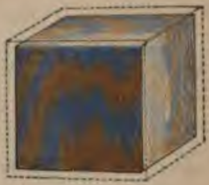


Fig. 202.

Suppose Fig. 202 to represent a cube formed of any substance, and let the length of each edge of the cube be unity at zero; the volume is consequently equal to 1, and the area of any one of the faces is also represented by 1. If the body be heated to any temperature t, each of the edges will increase by a certain quantity l, and the area of each face will become $(1+l)^2 = 1 + 2l + l^2$, while the volume of the cube will become

$$(1+l)^3 = 1 + 3l + 3l^2 + l^3.$$

But as the quantity l, which represents the linear expansion, is always very small, we may, without sensible error, neglect its second and third powers in comparison with its first power. We thus see that the increase in area of one of the faces of the cube is sensibly equal to $2l$, and that the increase in volume is sensibly equal to $3l$, which proves the propositions. These propositions evidently hold for the coefficients of expansion, so that we may say that *the coefficient of linear expansion is equal to one-third of the coefficient of cubical expansion, and to one-half of the coefficient of superficial expansion.*

The above demonstration supposes the body to remain similar to itself during expansion, which is not the case with bodies of a fibrous or laminated structure, nor with crystals, except those belonging to the cubic system.

198. Various Formulæ.—From equations (1) and (2) we may find the value of V in terms of V′, thus,

$$V=\frac{V'}{1+m}; \qquad (3)$$

$$V=\frac{V'}{1+Kt'} \qquad (4)$$

that is to say, given the volume of a body at a certain temperature, the volume at zero is found by *dividing the given volume by the factor of expansion.*

Formulæ (1), (2), (3), and (4) are particular cases of a more general formula. Let V and V′ be the volumes of the same body at temperatures t and t' respectively, U the volume at zero, K the coefficient of expansion, and m and m' the respective expansions between 0 and t, and 0 and t'. We then have, by formulæ (1) and (2),

$$V=U\ (1+m)=U\ (1+Kt)$$
$$V'=U\ (1+m')=U\ (1+Kt');$$

whence by division

$$\frac{V}{V'}=\frac{1+m}{1+m'}=\frac{1+Kt}{1+Kt'}, \qquad (5)$$

or *the volumes of the same body at different temperatures are proportional to the factors of expansion.*

The above formulæ are evidently applicable also to linear and superficial expansions.

199. Influence of Temperature upon Density.—As the density of a substance is inversely as the volume occupied by unit mass, it follows from last section that *the densities of the same substance at different temperatures are inversely as the factors of expansion,* so that if D, D′, D_0 denote the densities at the temperatures t, t', 0, then

$$D=\frac{D_0}{1+m}=\frac{D_0}{1+Kt}$$

$$D'=\frac{D_0}{1+m'}=\frac{D_0}{1+Kt'}$$

$$\frac{D}{D'}=\frac{1+m'}{1+m}=\frac{1+Kt'}{1+Kt}.$$

200. Correction of Specific Gravity for Temperature.—Let d be the density of a substance at temperature t° Cent., and d_0 its density at 0° C. Also, let D be the density of water at t° C., and D_4 its density at 4° C. (the temperature of maximum density). Then if the specific gravity of the substance be computed by comparing its density with that of water at the same temperature, as in the ordinary methods of experimental determination, the specific gravity thus obtained is $\frac{d}{D}$, and has different values according to the temperature at which the determination is made.

The specific gravity as commonly given in tables is the value of $\frac{d_0}{D_4}$; that is to say, is the ratio of the density of the substance at 0° C. to that of water at the temperature of maximum density. The tabular specific gravity is easily derivable from the observed specific gravity $\frac{d}{D}$, if the law of expansion of the substance be known; for if $1+m$ be the factor of expansion of the substance from 0° C. to t° C., and $1+e$ the factor of expansion of water from 4° C. to t° C., then

$$d_0 = d\,(1+m)$$
$$D_4 = D\,(1+e).$$

Hence,

$$\frac{d_0}{D_4} = \frac{d}{D}\,\frac{1+m}{1+e}, \text{ or the correcting factor required is } \frac{1+m}{1+e}.$$

In the case of solid bodies this correction is generally of little importance; but in determining the specific gravities of liquids, especially those which are very expansible by heat, it cannot be neglected.

201. Formulæ for the Expansion of Gases.—The volume of a gas depends both on the temperature and on the pressure to which it is subjected; hence the formulæ of expansion for this class of bodies are somewhat more complicated. Suppose we wish to find the relation between the volumes V and V′ of the same mass of gas at temperatures t and t', and under pressures P and P′ respectively. Let U be the volume of the given mass of gas at pressure P and temperature t', and let α be the coefficient of expansion of the gas.

The two volumes V and U, being under the same pressure, are proportional to the expansion factors corresponding to their temperatures (§ 198), which gives

$$\frac{V}{U} = \frac{1+\alpha t}{1+\alpha t'}.$$

The volumes U and V′, at the same temperature t', are, by Boyle's law, inversely proportional to the pressures; whence we have

$$\frac{U}{V'} = \frac{P'}{P}.$$

From these two equations we obtain by multiplication

$$\frac{V}{V'}=\frac{P'}{P}.\frac{1+at}{1+at'},\qquad (9)$$

which means that *the volumes assumed by the same mass of gas are inversely proportional to the pressures, and directly proportional to the expansion factors corresponding to the temperatures.*

From equation (9) we may easily deduce another equation, by remarking that the densities of the same quantity of gas must be inversely as the volumes occupied. Thus we have

$$\frac{D}{D'}=\frac{P}{P'}.\frac{1+at'}{1+at},\qquad (10)$$

which signifies that *the density of a gas varies directly as the pressure, and inversely as the expansion factor corresponding to the temperature.*

CHAPTER XXI.

EXPANSION OF SOLIDS.

202. Laplace and Lavoisier's Experiments.—Laplace and Lavoisier determined the linear expansion of a great number of solids by the following method.

The bar AB (Fig. 203) whose expansion is to be determined, has one end fixed at A, while the other can move freely, pushing before it the lever OB, which is movable about the point O, and carries a telescope whose line of sight is directed to a scale at some distance. It is evident that a displacement BB′ will correspond to a considerably greater length CC′ on the scale, which will increase with the distance of the scale from the telescope. The ratio of CC′ to BB′ is equal to the ratio of OC to OB, and is the same throughout the whole course of experiments. In order to determine this ratio once for all, we have only to measure the distance CC′ on the scale corresponding to a *known* displacement BB′.

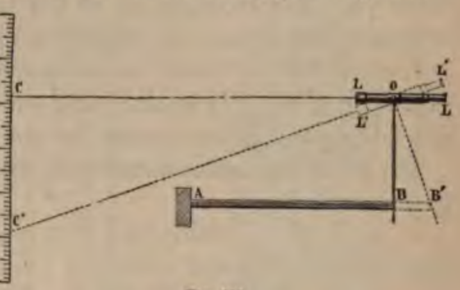


Fig. 203.
Principle of the Method of Laplace and Lavoisier.

The apparatus employed by Laplace and Lavoisier is shown in Fig. 204. The trough C, in which is laid the bar whose expansion is to be determined, is placed between four massive uprights of hewn stone N. One of the extremities of the bar rests against a fixed bar B′, firmly joined to two of the uprights; the other extremity pushes the bar B, which produces the rotation of the axis aa'. This axis carries with it in its rotation the telescope LL′, which is directed to the scale. The first step is to surround the bar with melting ice, and then observe the number on the scale marked by the line of sight of the telescope. The temperature of the trough is then raised, and the corresponding increase of length is measured.

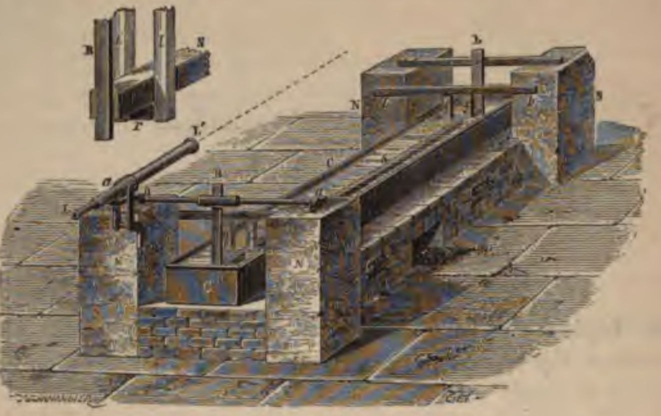


Fig. 204.—Apparatus of Laplace and Lavoisier.

Laplace and Lavoisier have discovered by this means that the expansion of solids is sensibly uniform between 0° and 100° C.; above this latter point it varies with the temperature.

The following table contains the most important results obtained by them:—

COEFFICIENTS OF LINEAR EXPANSION.

Gold, Paris standard, annealed,	0·000015153	Soft wrought iron, . . .	0·000012204
,, ,, unannealed,	0·000015515	Round iron, wire drawn, .	0·000012350
Steel not tempered, . . .	0·000010792	English flint-glass, . . .	0·000008116
Tempered steel reheated to 65°,	0·000012395	Gold, procured by parting, .	0·000014660
Silver obtained by cupellation,	0·000019075	Platina, ...	0·000009918
Silver, Paris standard, . .	0·000019086	Lead, ...	0·000088483
Copper, ...	0·000017173	French glass with lead, . .	0·000008715
Brass, ...	0·000018782	Sheet zinc, ...	0·000029416
Malacca tin, ...	0·000019376	Forged zinc, ...	0·000031083
Falmouth tin, ...	0·000021729		

A simpler and probably more accurate method of observing expansions was employed by Ramsden and Roy. It consists in the direct observation of the distance moved by either end of the bar, by means of two microscopes furnished with micrometers, the microscopes themselves being attached to an apparatus which is kept at a constant temperature by means of ice.

203. Compensating Pendulum.—The pendulum, as we know, regulates the motion of a clock. Suppose the clock to keep exact time at the temperature of zero; then if the temperature rises the length of the pendulum will increase, and with it the duration of each oscillation, so that the clock will lose. The opposite effect would be produced by a fall of the temperature below zero. We thus see that clocks are liable to go too fast in winter, and too slow in summer, and that we must move the bob of the pendulum from time to time in order to insure their regularity.

The effect of temperature may be notably diminished by means of compensating pendulums, of which there are several different kinds.

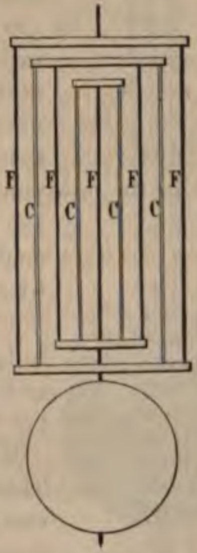


Fig. 205.
Plan of Gridiron Pendulum.

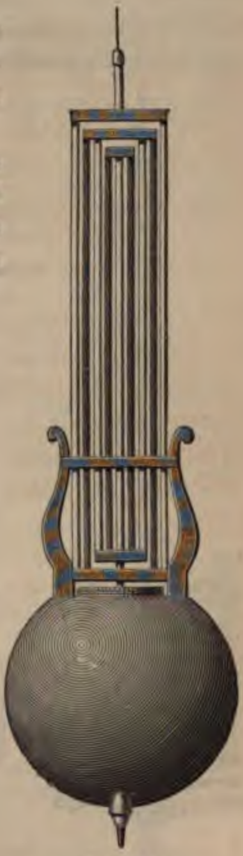


Fig. 206.
Gridiron Pendulum.

1. *Harrison's Gridiron Pendulum.*—This consists of four oblong frames, the uprights of which are alternately of steel F and of brass C (Fig. 205); the brass uprights rest upon the bottom of the steel frames, and to the top of the second brass frame is attached the steel rod carrying the bob. From this arrangement it follows that the effect of the lengthening of the steel rods will be to lower the bob, while that of the lengthening of the brass rods will be to raise it. It will be seen that these two effects may be made completely to neutralize each other; we have only to insure that the whole expansion of the steel shall be equal to that of the brass.[1] If L and L′ be the

---

[1] As the weight of the frame cannot be altogether neglected, and the change of dimensions produced by expansion affects the moment of inertia, the condition of compensation stated in the text can only be taken as approximate.

sum of the lengths of the steel and brass rods respectively; then this neutralization will be effected if $LKt=L'K't$, or if $LK=L'K'$, where K and K′ are the respective coefficients of expansion of steel and brass.

From the table on page 270 we learn that K is about $\frac{2}{3}$ K′; thus the sum of the lengths of the brass rods must be about $\frac{2}{3}$ of that of the steel rods. This result shows that we must have at least *two* brass frames, for with only one the compensating effect could not be produced, as the length of the steel rods would in that case be about double that of the brass. If we wish to have only a single frame of each different metal, we must choose two whose difference of expansion is much more marked; such, for instance, as iron and zinc, which are employed in Jurgensen's pendulum.

In order that the compensation may be complete, the centre of oscillation (§ 46) must remain at the same distance from the centre of suspension. The screw above the bob, shown in Fig. 206, enables us to attain this end by slightly raising or depressing the bob, and is intended to be used once for all to adjust the pendulum to the proper rate.

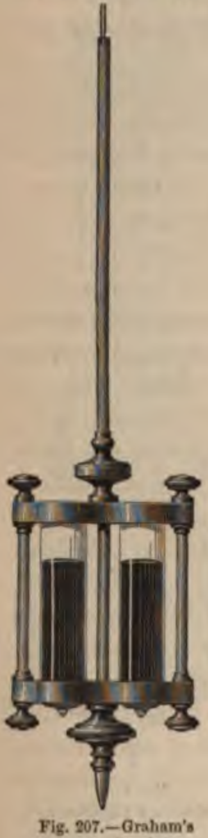


Fig. 207.—Graham's Mercurial Pendulum.

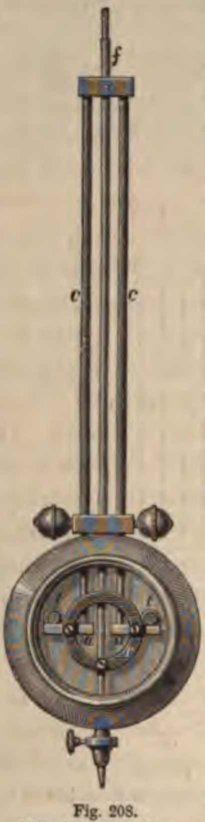


Fig. 208. Ellicott's Pendulum.

2. *Graham's Pendulum.*—This consists of an iron rod carrying at its lower end a frame, in which are fixed one or two glass cylinders containing mercury. When the temperature rises the lengthening of the rod lowers the centre of gravity and centre of oscillation of the whole; but the expansion of the mercury produces the contrary effect; and it will readily be understood that the quantity

of mercury in the cylinders may be such as to produce an approximately perfect compensation.

3. *Ellicott's Pendulum.*—This pendulum, which was invented in England in the last century, is known in France as Brocot's pendulum, and is frequently used in small French clocks. The main rod *f* is of iron. Attached to a cross-bar at the upper part of this rod are two brass rods *cc*, which, by means of the levers *aa* and the pins *tt*, attached to the bob, raise this latter when the temperature rises. The arms of the levers may evidently be so chosen as to maintain the centre of oscillation at an invariable distance from the axis of suspension, by means of the different expansive powers of iron and brass.

204. Force of Expansion of Solids.—The *force* of expansion is very considerable, being equal to the force necessary to compress the body to its original dimensions. Thus, for instance, iron when heated from 0° to 100° increases by ·0012 of its original length. In order to produce a corresponding change of length in a rod an inch square, a force of about 15 tons would be required. It would be useless to attempt to offer any mechanical resistance to a force so enormous; the only thing that can be done, in the case of structures in which metals are employed, is to arrange the parts in such a manner that the expansion shall not be attended with any evil effects. Thus, in a railway, the rails do not touch each other, a small interval being left to allow room for the variations of length. Iron beams employed in buildings must have the end free to move forward without encountering any obstacles, which they would inevitably overthrow. Sheets of zinc and lead employed in roofing, are so arranged as to be able in a certain extent to overlap each other on expansion.

We may further remark that the expansion of metals, though relatively very small, may practically become very considerable, if the length of metal which expands is sufficiently great. Suppose we take as an instance the length of railway from London to Edinburgh, which is about 400 miles. The extreme variations of temperature from winter to summer are about 50° C., which would produce a variation of length amounting to $400 \times 5280 \times \cdot 00061 = 1288$ feet. The actual variation is very considerable, and if the rails formed a continuous line at a certain temperature, this line would be interrupted or broken in pieces upon a change of temperature occurring in either direction.

205. Conversion of Heat into Work.—In conclusion, we may remark that heat when applied to a bar of metal produces two distinct and separate effects; one shown in the rise of temperature, and the other in the increase of volume. We may reasonably suppose that if the solid body were heated under such conditions as to preclude its expansion, the same quantity of heat would produce a much greater thermometric effect than in the former case. A similar remark applies to liquids and gases, and can be easily verified by experiment in the case of these latter. Here, then, is the first instance of a physical phenomenon of very frequent occurrence, namely, the conversion of heat into work, or reciprocally, of work into heat. Whenever a quantity of heat appears to be lost, the reason is that a corresponding amount of work is produced. If, on the other hand, work is done in compressing a body, so as to reduce it to the volume which it would occupy at a lower temperature, a rise of temperature is necessarily produced.

CHAPTER XXII.

EXPANSION OF LIQUIDS.

206. Relation between Real and Apparent Expansion.—If a vessel containing a liquid be heated, the level of the liquid rises, in consequence of the excess of the expansion of the liquid over that of the vessel. The observed increase of volume, not corrected for the expansion of the vessel, is called the apparent expansion. It is evidently less than the real expansion, for if the volume of the vessel had remained the same, the level would have risen higher.

The coefficients of real and apparent expansion are connected with the coefficient of expansion of the vessel by a very simple relation.

Let us take the case of a liquid contained in a vessel similar to a thermometer in shape, that is, suppose the tube to be divided into parts of equal capacity, and that we know by previous gauging how many divisions are equivalent to the volume of the reservoir.

Let n_0 denote the number of divisions occupied by the liquid at zero, and n_t the number of divisions occupied at temperature $t°$.

Then $\frac{n_t}{n_0}$ is the factor of apparent expansion, and $\frac{n_t}{n_0}-1$ is the apparent expansion.

Let us, for simplicity, take for our unit of volume the volume of a division at zero. Then if K be the expansion of the glass, the volume of a division at $t°$ will be $1+\mathrm{K}$.

The volume of the liquid at $t°$ is n_t of these divisions, and is therefore $n_t\,(1+\mathrm{K})$.

But if m be the real expansion of the liquid, the volume at $t°$ is $(1+m)\,n_0$, since n_0 is the volume at zero.

Hence we have

$$n_t\,(1+\mathrm{K})=(1+m)\,n_0;$$

and

$$\frac{n_t}{n_0}=\frac{1+m}{1+\mathrm{K}}.$$

That is, *the factor of apparent expansion is equal to the factor of real expansion of the liquid divided by that of the vessel.* Denote the factor of apparent expansion by $1+\Delta$.

Then since from above

$$1+\Delta=\frac{1+m}{1+K},$$

we have

$$1+m=(1+\Delta)(1+K)=1+\Delta+K+\Delta K;$$

whence

$$m=\Delta+K+\Delta K;$$

or since ΔK is much smaller than either Δ or K, and may in general be neglected,

$$m=\Delta+K.$$

That is, the real expansion of the liquid is equal to the apparent expansion plus the expansion of the vessel; and consequently, *the coefficient of real expansion is equal to the coefficient of apparent expansion plus the coefficient of expansion of the vessel.*

207. Expansion of Glass.—By means of this relation we can find the coefficient of expansion of any kind of glass; we have only to measure the coefficient of apparent expansion of the mercury in a thermometer made of this glass, and to subtract it from the coefficient of absolute expansion of the metal, which, as we shall see afterwards, is equal to $\frac{1}{5550}$. The coefficient of apparent expansion varies a little according to the quality of the glass employed; if we take it as $\frac{1}{6480}$, which is Dulong and Petit's determination of its mean value, we shall have for the coefficient of expansion of glass

$$K=\frac{1}{5550}-\frac{1}{6480}=\frac{1}{38700}.$$

208. Expansion of any Liquid.—The coefficient of expansion of the glass of which a thermometer is composed being known, we may use the instrument to measure the expansion of any liquid. For this purpose, the liquid whose coefficient of expansion is to be determined is introduced into the thermometer, and the number of divisions n_0 and n_t occupied by the liquid at the temperatures 0° and $t°$ respectively, are observed. Then, if D, Δ, K, be the coefficients of real expansion, of apparent expansion, and of expansion of the glass, each reckoned per degree Centigrade, we have

$$\frac{n_t}{n_0}-1=\Delta t, \text{ whence } \Delta \text{ is known; and}$$

$1+D=(1+\Delta)(1+K)$, or $D=\Delta+K$ nearly, whence D is known.

M. Pierre has performed an extensive series of experiments by this method upon a great number of liquids.

The apparatus employed by him is shown in Fig. 209. The thermometer containing the given liquid is fixed beside a mercurial thermometer, which marks the temperature. The reservoir and a small part of the tube are immersed in the bath contained in the cylinder below. The upper parts of the stems are inclosed in a second and smaller cylinder, the water in which is maintained at a sensibly constant temperature indicated by a very delicate thermometer.

From these experiments it appears that the expansions of liquids are in general much greater than those of solids. Further, expansion does not proceed uniformly, as compared with the indications of a mercurial thermometer, but increases very perceptibly as the temperature rises. This is shown by the following table:—

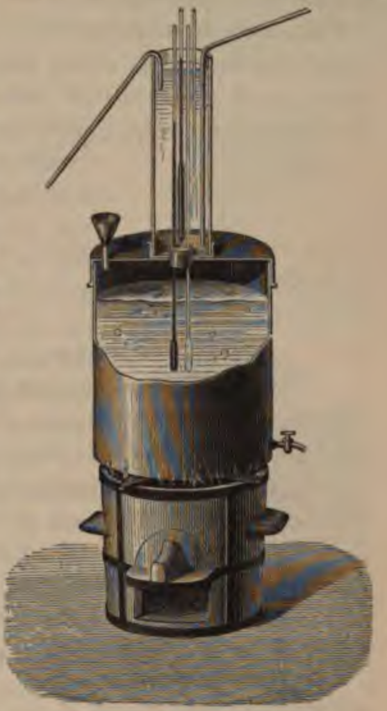


Fig. 209.—Pierre's Apparatus.

	Volume at 0°.	Volume at 10°.	Volume at 40°.
Water.....................	1	1·000146	1·007492
Alcohol...................	1	1·010661	1·044882
Ether	1	1·015408	1·066863
Bisulphide of carbon...	1	1·011554	1·049006
Wood-spirit.............	1	1·012020	1·050509

209. Maximum Density of Water.—By applying the experimental method just described to the case of water, we may easily observe the volume occupied by the same weight of this liquid at different temperatures, and it has thus been found that this volume is least at 4° Centigrade. At this temperature, accordingly, the density of water is a maximum, so that if a quantity of water at this temperature be either heated or cooled it undergoes an increase of volume. This is a curious and unique exception to the general law of expansion by heat.

This anomaly may be exhibited by means of the apparatus represented in Fig. 210, which consists of two thermometers, one of alcohol, and the other of water. The reservoir of this latter, on account of the smaller expansive power of the liquid, is a long spiral, enveloping that of the alcohol thermometer. Both the reservoirs are contained in a metal box, which is at first filled with melting ice. The two instruments are so placed, that at zero the extremities of the two liquid columns are on the same horizontal line. This being the case, if the ice be now removed, and the apparatus left to itself, or if the process be accelerated by placing a spirit-lamp below the box, the alcohol will immediately be seen to rise, while the water will descend; and the two liquids will thus continue to move in opposite directions until a temperature of about 4° is attained. From this moment the water ceases to descend, and begins to move in the same direction as the alcohol. This experiment, although very well adapted for exhibiting the phenomenon, does not enable us to measure exactly the temperature of maximum density, since it is the apparent, and not the real, expansion of water which is thus observed. The following experiment, which is due to Hope, is more rigorous.

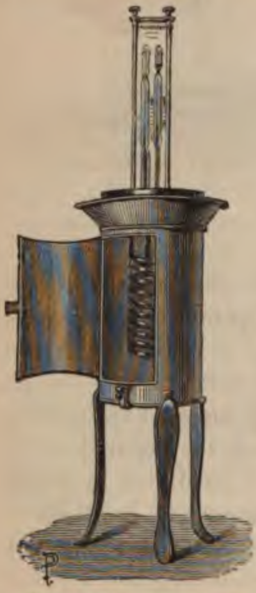


Fig. 210.—Maximum Density of Water.

A glass jar is employed, having two lateral openings, one near the top and the other near the bottom, which admit two thermometers placed horizontally. The tube is filled with water, and its middle is surrounded with a frigorific mixture. The following phenomena will then be observed.

The lower thermometer descends steadily to 4°, and there remains stationary. The upper thermometer at first undergoes very little change, but when the lower one has reached the fixed temperature, the upper one begins to fall, reaches the temperature of zero, and, finally, the water at the surface freezes, if the action of the frigorific mixture continues for a sufficiently long time. These facts admit of a very simple explanation.

As the water in the middle portion of the tube grows colder its density increases, and it sinks to the bottom. This process goes on till all the water in the lower part of the vessel has attained the temperature of 4°. But when all the water from the centre to the bottom has attained this temperature, any further cooling of the water in the centre fails to produce motion, until needles of ice are formed. These being specifically lighter than water, rise to the surface, and thus produce a circulation which causes the water near the surface to freeze, while that near the bottom remains at the temperature of 4°.

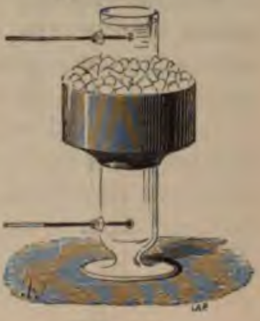


Fig. 211.
Hope's Experiment.

This experiment represents on a small scale what actually takes place during winter in pools of fresh water. The fall of temperature at the surface does not extend to the bottom of the pool, where the water, whatever be the external temperature, seldom falls below 4°. This is a fact of great interest, as exemplifying the close connection of natural phenomena, and the manner in which they contribute to a common end. It is in virtue of this anomaly exhibited by water in its expansion, taken in conjunction with the specific lightness of ice and the low conducting power of water, that the temperature at the bottom of deep pools remains moderate even during the severest cold, and that the lives of aquatic animals are preserved.

210. Saline Solutions.—In the case of saline solutions of different densities, the temperature of maximum density falls along with the freezing-point, and in fact falls more rapidly than this latter, so that for solutions containing a certain proportion of salt the temperature of maximum density is below the freezing-point. In order to show this experimentally, the solution must be placed in such circumstances as to remain liquid at a temperature below its freezing-point. This is a curious example of the continuity of physical laws, and of the restriction which must be applied in physics to the generally correct and logical principle of final causes. For salt water has a point of maximum density, although before that point is reached congelation takes place. In this instance the maximum density plays no part in the designs of nature, and leads to no practical benefit, being simply a proof of the permanence of a physical law, even when the circumstances on which its utility depended have disappeared.

211. Law of the Expansion of Liquids.—As we have shown above (§ 208), the expansion of liquids does not advance uniformly with the temperature; whence it follows that the mean coefficient of expansion will vary according to the limiting temperatures between which it is taken.

From a general review of the researches which have been made on this subject, it appears that for a great number of liquids the mean coefficient of expansion increases uniformly with the temperature. If, therefore, Δ be the expansion from 0 to t, we have

$$\frac{\Delta}{t} = a + bt, \text{ whence } \Delta = at + bt^2,$$

a and b being two constants specifying the expansibility of the given liquid.

For some very expansible liquids two constants are not sufficient, and the expansion is represented by the formula

$$\Delta = at + bt^2 + ct^3.$$

We subjoin a few instances of this class taken from the work of M. Pierre:—

Alcohol.................... $\Delta = 0{\cdot}0010486\, t + 0{\cdot}0000017510\, t^2 + 0{\cdot}00000000134518\, t^3$
Ether........................ $\Delta = 0{\cdot}0015132\, t + 0{\cdot}0000023592\, t^2 + 0{\cdot}000000040051\, t^3$
Bisulphide of carbon.... $\Delta = 0{\cdot}0011398\, t + 0{\cdot}0000013707\, t^2 + 0{\cdot}00000019123\, t^3$
Bromine... .... $\Delta = 0{\cdot}0010382\, t + 0{\cdot}0000017114\, t^2 + 0{\cdot}0000000054471\, t^3$

An examination of the formulæ for the different liquids which have been tested, shows that none of them have a point of maximum density; this property remains peculiar to water.

212. Absolute Expansion of Mercury.—The great importance of mercury in physical experiments, especially in connection with the barometer and thermometer, render it necessary to determine very accurately the coefficient of expansion of this liquid. This determination has been effected by Dulong and Petit by a very ingenious method, in which the observation of the heights of liquid columns is substituted for the measurement of volumes, which is always open to some uncertainty.

A and B are two tubes containing mercury, and communicating with each other by a very narrow tube CD. If the temperature of the liquid be uniform, the mercury should stand at the same height in both branches, according to the fundamental law of liquids in communicating vessels. But if the tube AC, for instance, be kept at 0° Cent., and the temperature of BD be raised, the density of the heated liquid will become less, and a greater height will consequently be required to equilibrate the pressure of the other column.

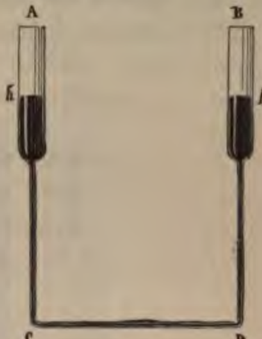


Fig. 212.—Principle of Dulong's Method.

Suppose the horizontal tube divided by a vertical section, and let h and h' denote the respective heights of the liquid in the cold and in the heated branches above the centre of gravity of this section. As the pressures on both sides must be equal, we must have the equation $hd = h'd'$, where d and d' are the densities of the mercury at zero and at the other given temperature.

But from what has been said above (§ 199), we have $d' = \frac{d}{1+m}$, where m is the expansion of the liquid from 0° to $t°$; and consequently, $hd = \frac{h'd}{1+m}$, whence

$$m = \frac{h' - h}{h}.$$

We thus see that it is sufficient to measure exactly the heights h' and h in order to find m.

We should remark, that the centre of gravity of the liquid section which we have been considering, is the only point of it which is in equilibrium; the upper part is subject to a greater pressure on the side of the heated liquid, and the lower part on the side of the cold; there is thus a tendency to the production of two opposite currents, which, however, is almost completely destroyed by the smallness of the bore of the connecting tube. Even supposing these currents actually to exist, the inverse effects produced by them would sensibly compensate each other, compared with the heights of the liquid in the two branches.

The following is the method by which Dulong and Petit have carried out the above principle.

The connecting tube, between the two branches A and B of the apparatus (Fig. 213), rests upon a T-shaped iron support, carrying two spirit-levels at right angles to each other for insuring horizontality. One of the branches B is inclosed in a cylinder containir melting ice; the other A is surrounded by a copper cylinder filled with oil, and heated by a furnace connected with the apparatus. In making an observation the first step is to arrange the apparatus so that, when the oil is heated to the temperature required, the mercury in the tube A may just be seen above the top of the cylinder, so as to be sighted with the telescope of a cathetometer; this may be effected by adding or taking away a small quantity of oil. The extremity of the column B is next sighted, which gives the difference of the heights h' and h. It is further necessary to determine the absolute height h.

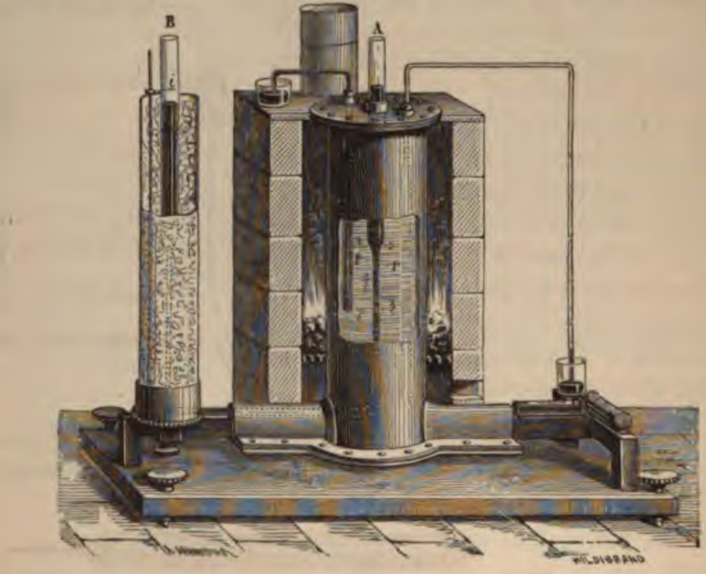


Fig. 213.—Apparatus of Dulong and Petit.

For this purpose the height of a reference mark i above the surface of the T-shaped support has been directly measured. From this height half the external diameter of the horizontal tube is to be subtracted, and it only remains to observe the distance of the end of the column B from the mark at the time of the experiment.

The temperature of the oil is given by the weight-thermometer t, and by the air-thermometer r, which latter we shall explain hereafter.

By means of this method Dulong and Petit ascertained that the expansion of mercury is sensibly uniform, as compared with the indications of an air-thermometer, between 0° and 100° C. Above this point it goes on increasing like other liquids, but not in any marked degree. Thus, the mean coefficient between 0° and 100° is $\frac{1}{5550}$. Between 0° and 200° it becomes $\frac{1}{5425}$, and $\frac{1}{5300}$ between 0° and 300°.

Regnault, without altering the principle of the experiments of Dulong and Petit, introduced several improvements into their apparatus, and added greatly to the length of the tubes A and B, thereby rendering the apparatus more sensitive. The results obtained by him do not differ very materially from those of Dulong and Petit; thus, for instance, he makes the coefficient between 0° and 100° equal to $\frac{1}{5509}$.

His experiments show that the mean coefficient between 0° and 50° is $\frac{1}{5547}$, a number almost identical with $\frac{1}{5550}$.

213. Expansion of Iron and Platinum.—The coefficient of absolute expansion of mercury being known, that of glass is deduced from it in the manner already indicated (§ 207). Dulong and Petit have deduced from it also the coefficients of expansion of iron and platinum, neither of which metals are attacked by mercury. The method employed is the following.

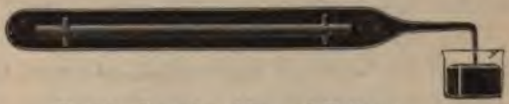


Fig. 214.—Expansion of Iron and Platinum.

The metal in question was introduced, in the shape of a cylindrical bar, into the reservoir of a weight-thermometer. Let W be the weight of the metal introduced, and D its density at zero. The process is the same as in using the weight-thermometer; that is, after having filled the reservoir with mercury at 0° C., we observe the weight w of the metal which issues at a given temperature t. The volume at 0° C. of the mercury which has issued, is $\frac{w}{d}$, d being the density of mercury at zero; the volume at $t°$ is therefore $\frac{w}{d}(1+mt)$, m being the coefficient of expansion of mercury. This volume evidently represents the expansion of the metal, *plus* that of the mercury, *minus* that of the glass. If then M denote the weight of mercury that fills the apparatus at 0° C., and if K be the coefficient of cubical expansion of glass, and x the expansion of unit volume of the given metal, we have the equation

$$\frac{w}{d}(1+mt)=\frac{\mathrm{W}}{\mathrm{D}}x+\frac{\mathrm{M}}{d}mt-\left(\frac{\mathrm{W}}{\mathrm{D}}+\frac{\mathrm{M}}{d}\right)\mathrm{K}t,$$

whence we can find x.

214. Convection of Heat in Liquids.—When different parts of a liquid are heated to different temperatures, corresponding differences of density arise, leading usually to the formation of currents which tend to produce equality of temperature as far as their presence extends. To this phenomenon, which is altogether distinct from conduction, the name of *convection* is given.

Thus, for instance, if we apply heat to the bottom of a vessel containing water, the parts immediately subjected to the action of the heat expand and rise to the surface; they are replaced by colder layers, which in their turn are heated and ascend; and thus the process continues indefinitely. The two currents can be very well shown by throwing some oak saw-dust into the water. By the movements of this substance, which has nearly the same density as water, it will be seen that the ascending current occupies the centre of the vessel, while the descending current passes along the sides.

215. Heating of Buildings by Hot Water.—This is a simple application of the principle just stated. One of the most common arrangements for this purpose is shown in Fig. 215; it is called the high-pressure system, because the water in the boiler can acquire a temperature considerably above 100° C. The boiler C is heated by a fire below it, and the products of combustion escape through the chimney A B. At the top of the house is a reservoir D, communicating with the boiler by a tube. From this reservoir the liquid flows into another reservoir E in the story immediately below, thence into another reservoir F, and so on. Finally, the last of these reservoirs communicates with the bottom of the boiler. The boiler, tubes, and reservoirs are all completely filled with water, with the exception of a small space left above in order to give room for the expansion of the liquid. An ascending current flows through the left-hand tube, and the circulation continues with remarkable regularity, so long as the temperature of the water in the boiler remains constant.

216. Currents in the Sea.—In the production of these currents convection plays an important, though perhaps not the principal part. In fact, the sea is an enormous mass of liquid whose temperature varies from point to point. Equilibrium is consequently impossible, and the different parts must therefore be in a state of continual motion with regard to each other. The waters of the tropical seas should, by reason of their excess of temperature, have a higher level than those of the polar seas; and the result is, a continual kind of overflowing of the waters about the equator, and consequently a vast current setting towards the poles. But to this current evidently corresponds a lower current of cold water flowing towards the equator, there to become heated, to overflow again, and so on. One of the most remarkable of oceanic currents is that which is known as the *Gulf Stream.* This current of warm water forms a kind of immense river in the midst of the sea, differing in the temperature, saltness, and colour of its waters from the medium in which it flows. Its origin is in the Gulf of Mexico, whence it issues through the straits between the Bahamas and Florida, turns to the north-west, and splits into two branches, one of which goes to warm the coasts of Ireland and Norway, the other gradually turns southwards, traverses the Atlantic from north to south, and finally loses itself in the regions of the equator.

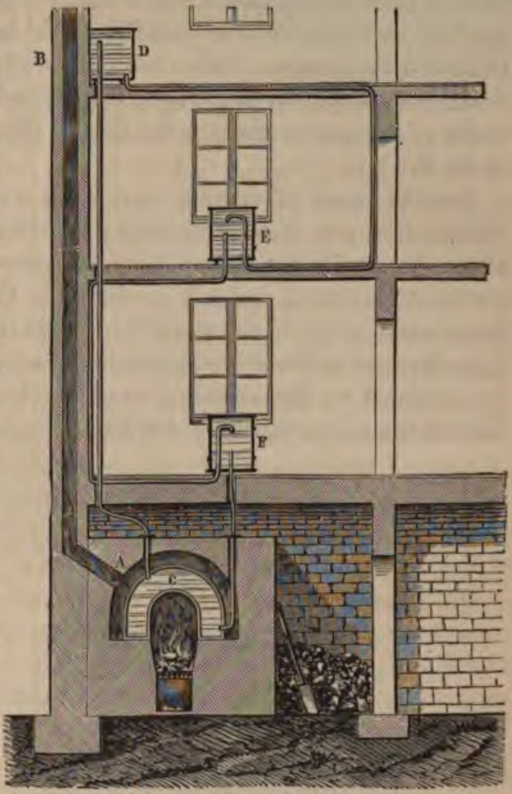


Fig. 215.—Heating by Hot Water.

"The Gulf Stream is a river in the ocean; in the severest droughts it never fails, and in the mightiest floods it never overflows; its banks and its bottom are of cold water, while its current is of warm; it takes its rise in the Gulf of Mexico, and empties into Arctic seas. There is on earth no other such majestic flow of waters. Its current is more rapid than the Mississippi or the Amazon, and its volume more than a thousand times greater. Its waters, as far out from the Gulf as the Carolina coasts, are of indigo blue. They are so distinctly marked that their line of junction with the common sea-water may be traced by the eye. Often one-half of the vessel may be perceived floating in Gulf Stream water, while the other half is in common water of the sea, so sharp is the line."—(Maury, *Physical Geography of the Sea.*)

Another cause of oceanic currents is to be found in the winds, which again are themselves examples of convective currents in the atmosphere. In the case of the Gulf Stream, it would appear that an accumulation of water is produced in the Gulf of Mexico by the trade-wind which blows steadily towards it over the South Atlantic. The elevation of level occasioned by this accumulation is probably to be regarded as the principal cause of the Gulf Stream. We shall discuss the origin of winds in a later chapter (Chap. xxxiv.)

CHAPTER XXIII.

EXPANSION OF GASES.

217. Experiments of Gay-Lussac.—Gay-Lussac conducted a series of researches on the expansion of gases, the results of which were long regarded as classical. He employed a thermometer with a large reservoir A, containing the gas to be operated on; an index of mercury *mn* separated the gas from the external air, while leaving it full liberty to expand. The gas had previously been dried by passing it through a tube containing chloride of calcium, or some other desiccating substance. The thermometer was fixed in a vessel which was first filled with melting ice, and when the gas had thus been brought to 0° C., the tube was so adjusted that the index coincided with the opening through which the thermometer passed.

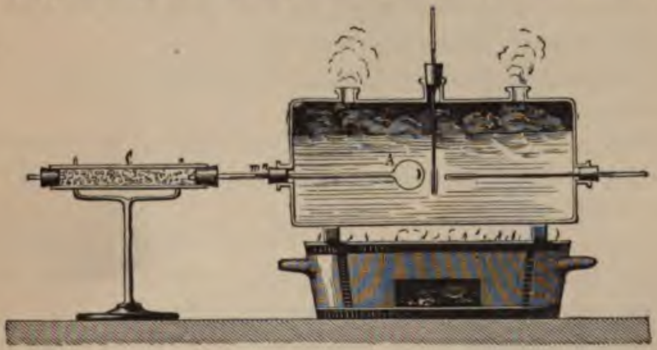


Fig. 216.—Gay-Lussac's Apparatus.

The tube being divided into parts of equal capacity, and the reservoir having been previously gauged, the volume V is known which is occupied by the gas at an external pressure H indicated by a barom[illegible] [illegible]e apparatus is then raised to a given temperature T by means of the furnace below the vessel, and the stem of the thermometer is moved until the index reaches the edge of the opening; at this new temperature the gas occupies a volume V' expressed in divisions of the tube: at the same time the pressure may have varied; suppose it to have become H'. From these data it is easy to deduce the expansion of unit volume of the gas from 0° to T at constant pressure. If D denote this expansion, the volume of the gas at T at the original pressure would be $V(1+D)$. But the gas occupies a volume V' at the temperature T and pressure H'. At the pressure H the volume would therefore be $V'\frac{H'}{H}$. But the divisions of the thermometer have expanded in the ratio $1+KT$, K being the coefficient of expansion of glass: the true expression therefore for the new volume of the gas at the pressure H is $\frac{V'(1+KT)H'}{H}$; whence we have the equation

$$V(1+D) = V'(1+KT)\frac{H'}{H},$$

from which we can find the value of D, and consequently that of the mean coefficient of expansion $\frac{D}{T}$. By means of this method Gay-Lussac arrived at the following results:—

1st.—All gases expand by the same amount between the same limits of temperature.

2d.—The coefficient of expansion is independent of the pressure. He also found that the coefficient of expansion of air between 0° and 100° was ·00375.

These laws, which, together with Boyle's law, were long regarded as defining the fundamental properties of the gaseous state, are not rigorously exact, but are subject to restrictions similar to those which apply to Boyle's law. The absolute value of the co-efficient of expansion of air as laid down by Gay-Lussac is very sensibly erroneous. The true value has been determined, by subsequent experiments conducted with greater precision, to be ·003665, or $\frac{1}{273}$.

218. Regnault's Experiments.—The apparatus employed by Gay-Lussac had one serious imperfection. The mercurial index did not constitute a sufficient barrier between the gas under investigation and the external air; so that a portion of the gas was able to escape, while at the same time some of the external air became mixed with the gas; either of which circumstances would impair the accuracy of the experiment. It also appears that the means employed by Gay-Lussac for desiccating the gas were insufficient. However this may be, the subject of the expansion of gases has been taken up by several physicists, as Pouillet, Rudberg, Magnus, and Regnault, who have performed a number of experiments on this subject, of undoubted accuracy, the result of which has been slightly to modify the conclusions arrived at by Gay-Lussac.

We shall confine ourselves to describing one of the methods employed by Regnault.

The apparatus consists of a glass ball with a narrow neck, containing the gas. This is placed in a boiler (Fig. 217), containing water, which can afterwards be raised to ebullition. A T-shaped tube, with three branches, establishes communication between the neck of the globe and a system, consisting of two tubes, containing mercury, and forming in fact a mercurial manometer, and also between the globe [illegible]ies of desiccating tubes, not shown in the figure,

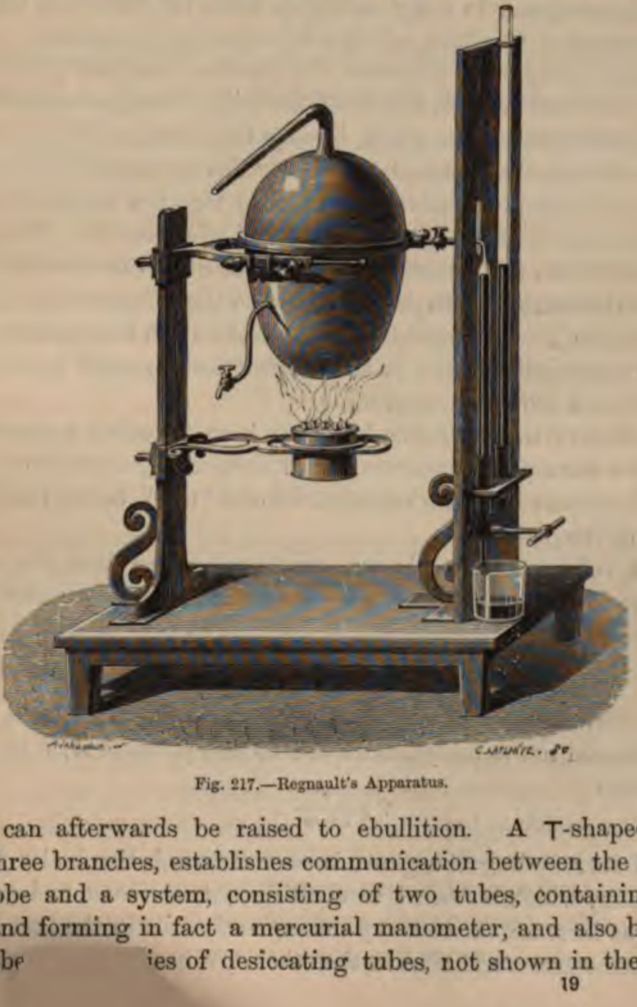


Fig. 217.—Regnault's Apparatus.

which are themselves in communication with a small air-pump. On the first branch of the manometer, near the capillary portion of the tube, is a reference mark.

The following is the mode of determining by means of this apparatus the coefficient of expansion between 0° and 100° C. The first step is to exhaust the globe a certain number of times, each time refilling it with air, or with the gas under investigation, which has been dried by passing it through the desiccating tubes. The drying may be rendered more complete and rapid by raising the temperature of the globe. This series of operations is, as Regnault has shown, absolutely necessary in order to remove from the surface of the glass the last traces of moisture, which are exceedingly tenacious.

The gas having been admitted for the last time, the globe is surrounded with melting ice, and is left to itself. The gas contracts, and a fresh portion enters the globe, having first been perfectly dried by passing through the desiccating tubes. The apparatus is thus filled with gas, and communication is established for a few seconds with the external air, so that the gas is at atmospheric pressure. Mercury is then poured into the manometer so as to bring the level of the fluid, which is the same in both branches, up to the reference mark. The branch of the ⊤ which established communication between the globe and the desiccating tubes is then hermetically sealed by directing the flame of a blowpipe upon it.

The effect of this operation has thus been to isolate a quantity of gas at the atmospheric pressure H. This quantity consists of—

(1.) A volume V at the temperature of 0° C., V being the known volume of the globe.

(2.) A volume v, which is very small, extending from the neck of the globe to the mark on the manometric tube. This volume v is at the surrounding temperature t; if brought to zero, it would become $\frac{v}{1+at}$, a being the coefficient of expansion of the gas. In the first part of the experiment, therefore, we have a quantity of gas which, when reduced to the temperature of zero and pressure H, would have the volume

$$V+\frac{v}{1+at}.$$

The ice surrounding the globe is now removed, the boiler is filled with water, which is heated to ebullition; the volume and pressure of the gas increase, the mercury consequently falls in the first branch of the manometer, and rises in the other. When equilibrium of temperature has been established, mercury is poured into the open branch, so as to raise that in the other branch to the mark. There is then found to be a difference of level h: the external pressure may have changed at the same time, and become H'; the gas is consequently subjected to a pressure $H'+h$. Its volume consists of two parts:—

(1.) The volume $V(1+KT)$ of the globe, K denoting the coefficient of expansion of the glass, and T the temperature of the boiling water at the moment of the experiment; this volume when reduced to zero becomes

$$\frac{V(1+KT)}{1+\alpha T}.$$

(2.) The volume v of the tube as far as the mark, which volume at zero becomes $\frac{v}{1+\alpha t'}$, where t' is the surrounding temperature. Thus, in the second part of the experiment, the given quantity of gas under the pressure $H'+h$, would, at the temperature of zero, occupy the volume

$$\frac{V(1+KT)}{1+\alpha T}+\frac{v}{1+\alpha t'}.$$

We have thus, by expressing that the volumes are inversely as the pressures,

$$(H'+h)\left\{\frac{V(1+KT)}{1+\alpha T}+\frac{v}{1+\alpha t'}\right\}=\left(V+\frac{v}{1+\alpha t}\right)H,$$

whence

$$1+\alpha T=\frac{V(1+KT)}{\left(V+\frac{v}{1+\alpha t}\right)\frac{H}{H'+h}-\frac{v}{1+\alpha t'}}.$$

To solve this equation we have recourse to a method frequently employed in physics, which is called the *method of successive approximations;* v being a very small quantity, is at first supposed to be zero; on this supposition the value of α is easily obtained. This value is then substituted in the correcting terms $\frac{v}{1+\alpha t'}$, $\frac{v}{1+\alpha t'}$, whence the real value of αT is deduced. Now T is the temperature at which the water boils, and is always known, as we shall see hereafter, if the external pressure is known.

In the experiment just described, the volume of the gas remains sensibly the same, and the effect of heat is shown by an increase of pressure. We might have proceeded differently, and caused the gas to expand under a constant pressure.

We shall not stop to describe the modified form of the apparatus which is adapted to this other mode of experiment; we shall only remark that the results obtained by the two processes do not exactly agree, as will be seen from the following table:—

COEFFICIENTS OF EXPANSION PER DEGREE CENTIGRADE.

	From experiments at constant volume.	From experiments at constant pressure.
Air	0·003665	0·003670
Nitrogen	0·003668	
Hydrogen	0·003667	0·003661
Carbonic oxide	0·003667	0·003669
Carbonic acid	0·003688	0·003710
Nitrous oxide	0·003676	0·003720
Cyanogen	0·003829	0·003877
Sulphurous acid	0·003845	0·003903

This table shows that each gas has its own coefficient of expansion, as we have already seen that each has its own coefficient of compressibility. Non-liquefiable gases, however, have nearly the same coefficient of expansion, a result which accounts for the conclusion arrived at by Gay-Lussac.

As regards the differences between the two sets of numbers, it is to be noted that the second set alone represent expansion as directly observed. The first set directly measure the increase of pressure which occurs when expansion is prevented. If Boyle's law were rigorously true, the two sets of results ought to be identical. In point of fact, it will be remarked that, except in the case of hydrogen, the numbers in the second column are larger than those in the first, indicating that the product of volume and pressure diminishes slightly as the pressure increases.

We may add that the coefficient of expansion increases very sensibly with the pressure; thus, between the pressures of one and of three atmospheres the coefficient of expansion of air varies from 0·00367 to 0·00369. This increase is still more marked in the case of liquefiable gases.

The coefficient of expansion per degree Fahrenheit is $\frac{5}{9}$ of the coefficient per degree Centigrade. For air or any non-liquefiable gas this may be taken as ·002036 or $\frac{1}{491}$.

219. Air-thermometer.—We have already stated, in connection with the mercurial thermometer, that the name *degree* (Centigrade) is given to the hundredth part of the apparent expansion of the mercury in the glass. As the different kinds of glass employed in the construction of these instruments have not the same law of expansion, it follows, as we have remarked, that mercurial thermometers are not rigorously comparable with each other, particularly above 100°.

The expansion of air being much more considerable than that of mercury, the variations caused by differences in the glass will be relatively less; for this reason (as well as for others which will be stated hereafter) the air-thermometer is employed to measure temperature in experiments of precision.

Any apparatus that will measure the expansion of air may serve as an air-thermometer; we have only to consider T as the unknown quantity in the expression $1+\alpha T$, writing for α the value of the coefficient of expansion given in last section.

M. Pouillet proposed to employ air in pyrometric investigations, and constructed an instrument to which he gave the name of air-pyrometer, and with which he performed some interesting experiments. Pouillet's pyrometer was very similar to Regnault's apparatus described above (§ 218); but the reservoir and part of the tube were of platinum, so as to be able to resist high temperatures. The indications of this instrument, however, could not be entirely relied on, since platinum has the property of condensing air upon its surface, and partially giving it out at high temperatures. At such temperatures, also, platinum becomes quite permeable to some of the gases of the furnace. For pyrometric purposes it is better to inclose the air in a porcelain vessel, as has been done by Deville and Troost.[1]

219A. Absolute Temperature. Absolute Zero.—If the air-thermometer be made the standard of temperature, equal differences of temperature will correspond to equal differences in the volume occupied by a given mass of air at constant pressure, the difference amounting to $\frac{1}{273}$ of the volume at 0° C. for each degree Centigrade, or to $\frac{1}{491}$ of the volume at 32° F. for each degree Fahrenheit.

---

[1] The following account of a pyrometer constructed by Regnault, on the principle of the air-thermometer, is given in Dr. B. Stewart's treatise on heat. "There is a kind of flask, either cylindrical or spherical, which may be either of cast or wrought iron, of platinum or of porcelain: the mouth is closed by a plate containing a small aperture. From 15 to 20 grammes of mercury are added to this flask, which is then placed in that part of the furnace the temperature of which we desire to know. The mercury soon boils, its vapour expels the air by the orifice, and the excess of mercurial vapour goes off by the same means. When the apparatus has acquired the temperature of the furnace the flask is withdrawn and made to cool rapidly, and the mercury which remains in the flask is weighed. It may be weighed directly, or if it contains impurity, it is dissolved in acid, and estimated as a precipitate. This weight is that of the vapour of mercury which filled the flask at the temperature of the furnace, and the volume of the flask, as well as the density of mercurial vapour being kn[illegible] nperature may thus be determined."

The lowest temperature that could thus be expressed is evidently −273° C. or −459° F., since at this temperature the given mass of air would be reduced to a mathematical point. This is often called the *absolute zero* of temperature, and temperatures reckoned from it are called *absolute temperatures.*

If C and F denote temperatures Cent. and Fahr. respectively, 273 + C and 459 + F will be the corresponding expressions for absolute temperature.

The statement of the relations between the volume, pressure and temperature of a given mass of air or other gas can be somewhat simplified by the employment of this term. These relations (assuming the correctness of Boyle's and Gay-Lussac's laws) are as follows:—

1. The volume varies directly as the absolute temperature, when the pressure is constant.

2. The pressure varies directly as the absolute temperature, when the volume is constant.

3. For all variations, the expression $\frac{VP}{T}$ remains constant in value, V denoting volume, P pressure, and T absolute temperature.

The subject of this section will be further discussed in Chap. xxxii.

220. Density of Gases.—The volume of gases, owing to their great expansibility and compressibility, is subject to enormous variations. Hence, in stating the *absolute density* of a gas, it is very important to specify the temperature and pressure at which we suppose it to be taken.

In stating the *specific gravity* or *relative density* of a gas as compared with dry atmospheric air, which is always adopted as the standard substance, it is to be understood that the gas is at the same temperature and pressure as the air with which it is compared; and, in consequence of the inexactness of the laws of Boyle and Gay-Lussac, it is further necessary, for purposes of accuracy, to specify the temperature and pressure at which the comparison is made. These are usually the temperature 0° C., and the pressure of 760 millimetres. The specific gravity or relative density of a gas is therefore defined as *the ratio of the weight of any volume of the gas at the temperature* 0° *C., and the pressure of* 760 *millimetres, to the weight of the same volume of dry air at the same temperature and pressure.*

This ratio being known, we can deduce from it the weight of any volume of the gas in question, by employing as a factor the weight of unit volume of air (§ 100). Thus, for instance, the ratio of the density of oxygen to that of air being 1·1056, and the weight of a litre of air at 0° C. and 760 millimetres being 1·293 gramme, we conclude that the weight of a litre of oxygen at this temperature and pressure is 1·293 × 1·1056 = 1·429 gramme.

221. Measurement of the Density of a Gas.—The densities of gases have been the subject of numerous investigations; we shall here mention only the ingenious and exact method employed by Regnault. The gas is inclosed in a globe, of about 12 litres' capacity, and furnished with a stop-cock. This communicates with a three-way tube, furnished with stop-cocks *a* and *b* (Fig. 218), and through it with an air-pump on one side, and a manometer on the other. The globe is exhausted several times, and each time the gas is dried on its way to the globe by passing through a number of tubes containing pieces of pumice-stone moistened with sulphuric acid. When all moisture is supposed to be removed, the globe is surrounded with melting ice, and is allowed to fill with gas at the pressure of the atmosphere. When equilibrium of temperature has been established, the globe is taken out, carefully dried, and suspended from one of the scales of a balance. From the other scale is suspended a globe *of the same glass*, and of the same external volume (Fig. 219). The equality of the volumes is tested by weighing each in water, and noting the upward pressure of the liquid in each case. Weights are now added until equilibrium is established; and it can be proved that this equilibrium [illegible] orously maintained, whatever be the variations of

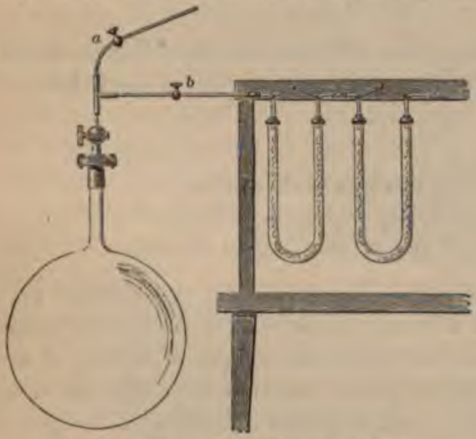


Fig. 218.—Measurement of Density of Gases.

Fig. 219.—Compensating Globe.

external pressure and temperature, because these variations will produce the same effect upon both globes. It is this introduction of a *compensating globe* which gives Regnault's method its great precision;[1] for since all external causes that could disturb equilibrium are balanced, the observed differences in weight can result only from variations in the gas inside.

The globe is then again surrounded with ice, communication with the air-pump and the manometer is established, and a partial vacuum is produced as far as a certain limit h. On the globe being again suspended from the scale, the equilibrium of the balance is disturbed, and the weight w, necessary to re-establish it, is evidently equal to the weight of a volume of dry gas at 0°, and at the pressure $H-h$, H being the external pressure. Hence it follows that the weight of dry gas which would completely fill the globe at the temperature of 0°, and at the pressure of 760 millimetres, is

$$w\frac{760}{H-h}.$$

The same experiment, when performed with air, would give as the weight of the same volume of this gas under the same conditions

$$w'\frac{760}{H'-h'}.$$

The relative density of the given gas is therefore

$$w\frac{760}{H-h}\div w'\frac{760}{H'-h'}=\frac{w}{w'}\cdot\frac{H'-h'}{H-h}.$$

222. Weight of a Litre of Air.—The preceding experiments give the weight of dry air which fills a given globe at 0°, and at a pressure of 760 millimetres. In order to know the weight of a litre of air, we have only to observe the weight of water which fills the same globe at a given temperature. Let m be the difference of weight of the globe when filled with water and with dry air; then the weight of the water contained in the globe is evidently m *plus* the weight of the dry air, which is previously known, and which we shall denote by a. Let x be the volume of the globe, and e the expansion of the water from 4° C. to the temperature of weighing. Then, if the gramme and cubic centimetre be the units of weight and volume, we have the equation

$$x\frac{1}{1+e}=m+a,$$

---

[1] The same device had previously been employed by Dr. Prout in determining the weight of air.

which gives the volume of the globe at a known temperature, whence the volume at zero may be deduced.

Various minute precautions are necessary in order to fill the globe with water completely free from air, and in order to insure that the temperature shall be the same throughout the whole of the considerable volume employed in the experiment. The first condition is especially difficult to fulfil; in order to attain it, Regnault first expelled the air from the globe by introducing a small quantity of water, and then exhausting the globe, the process being aided by a slight elevation of temperature; on the other hand, water, from which the air had been expelled by boiling, was forced by the pressure of steam into a tube leading to the stop-cock of the exhausted globe, so as to be nowhere exposed to the atmosphere. The difficulties of this process were skilfully overcome by Regnault, and he finally arrived at the following result.

In Paris, at a height of 60 metres above the level of the sea, a litre of dry air, at the temperature of 0° C., and a pressure of 760 millimetres, weighs 1·2932 gramme. A pressure of 760 millimetres of mercury has not the same effective value at different parts of the globe, on account of the variations in the intensity of gravity, whence it follows that the weight of the litre of air, defined by the preceding conditions, varies proportionally to the value of g. (See note to § 100.)

The following table gives the densities of several gases at 0° C., and under the pressure of 760 millimetres at Paris:—

Name of Gas.	Relative Density.	Absolute Density in grammes per litre.
Air	1	1·2932
Oxygen	1·10563	1·4298
Hydrogen	·06926	·08957
Nitrogen	·97137	1·25615
Chlorine	2·4216	3·1328
Carbonic oxide	·9569	1·2344
Carbonic acid	1·52901	1·9774
Protoxide of nitrogen	1·5269	1·9697
Binoxide of nitrogen	1·0388	1·3434
Sulphurous acid	2·1930	2·7289
Cyanogen	1·8064	2·3302
Marsh-gas	·559	·727
Olefiant gas	·985	1·274
Ammonia	·5967	·7697

223. Draught of Chimneys.—The expansion of air by heat produces the upward current in chimneys, and an approximate expression for the velocity of this current may be obtained by the application of Torricelli's theorem on the efflux of fluids from orifices (Chap. xviii.).

Suppose the chimney to be cylindrical and of height h. Let the air within it be at the uniform temperature t' Centigrade, and the external air at the uniform temperature t. According to Torricelli's theorem, the square of the linear velocity of efflux is equal to the product of $2g$ into the head of fluid, the term *head of fluid* being employed to denote the *pressure* producing efflux, *expressed in terms of depth of the fluid.*

In the present case this head is the difference between h, which is the height of air within the chimney, and the height which a column of the external air of original height h would have if expanded upwards, by raising its temperature from t to t'. This latter height is $h\frac{1+at'}{1+at}$; a denoting the coefficient of expansion ·00366; and the head is

$$h\frac{1+at'}{1+at}-h=\frac{ha\,(t'-t)}{1+at}.$$

Hence, denoting by v the velocity of the current up the chimney, we have

$$v^2=\frac{2gha\,(t'-t)}{1+at}$$

This investigation, though it gives a result in excess of the truth, from neglecting to take account of friction and eddies, is sufficient to explain the principal circumstances on which the strength of draught depends. It shows that the draught increases with the height h of the chimney, and also with the difference $t'-t$ between the internal and external temperatures.

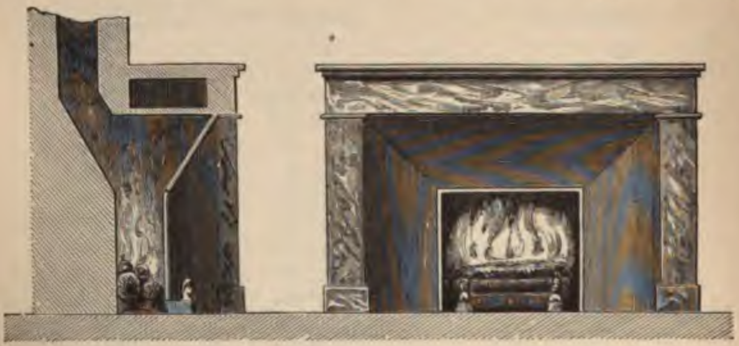


Fig. 220.—Rumford's Fire-place.

The draught is not so good when a fire is first lighted as after it has been burning for some time, because a cold chimney chills the air within it. On the other hand, if the fire is so regulated as to keep the room at the same temperature in all weathers, the draught will be strongest when the weather is coldest.

The opening at the lower end of the chimney should not be too wide nor too high above the fire, as the air from the room would then enter it in large quantity, without being first warmed by passing through the fire. These defects prevailed to a great extent in old chimneys. Rumford was the first to attempt rational improvements. He reduced the opening of the chimney and the depth of the fire-place, and added polished plates inclined at an angle, which serve both to guide the air to the fire and to reflect heat into the room (Fig. 220).

The blower (Fig. 221) produces its well-known effects by compelling all air to pass through the fire before entering the chimney. This at once improves the draught of the chimney by raising the temperature of the air within it, and quickens combustion by increasing the supply of oxygen to the fuel.

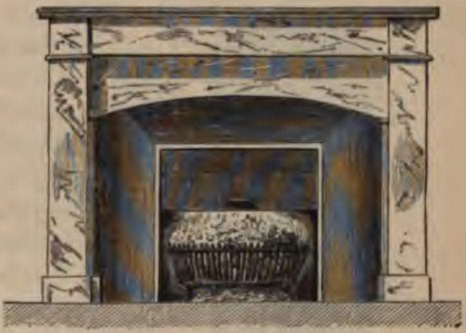


Fig. 221.—Fire-place with Blower.

224. Stoves.—The heating of rooms by open fire-places is effected almost entirely by radiation, and much even of the radiant heat is wasted. This mode of heating then, though agreeable and healthful, is far from economical. Stoves have a great advantage in point of economy, for the heat absorbed by their sides is in great measure given out to the room, whereas in an ordinary fire-place the greater part of this heat is lost. Open fire-places have, however, the advantage as regards ventilation; the large opening at the foot of the chimney, to which the air of the room has free access, causes a large body of air from the room to ascend the chimney, its place being supplied by fresh air entering through the chinks of the doors and windows, or any other openings which may exist.

Stoves are also liable to the objection of making the air of the room too dry, not, of course, by removing water, but by raising the temperature of the air too much above the dew-point (Chap. xxviii.). The same thing occurs with open fire-places in frosty weather, at which time the dew-point is unusually low. This evil can be remedied by placing a vessel of water on the stove. The reason why it is more liable to occur with stoves than with open fire-places, is mainly that the former raise the air in the room to a higher temperature than the latter, the defect of air-temperature being in the latter case compensated by the intensity of the direct radiation from the glowing fuel.

Fire-clay, from its low conducting power, is very serviceable both for the backs of fire-places and for the lining of stoves. In the former situation it prevents the wasteful escape of heat backwards into the chimney, and keeps the back of the fire nearly as hot as the centre. As a lining to stoves, it impedes the lateral escape of heat, thus answering the double purpose of preventing the sides of the stove from overheating, and at the same time of keeping up the temperature of the fire, and thereby promoting complete combustion. Its use must, however, be confined to that portion of the stove which serves as the fire-box, as it would otherwise prevent the heat from being given out to the apartment.

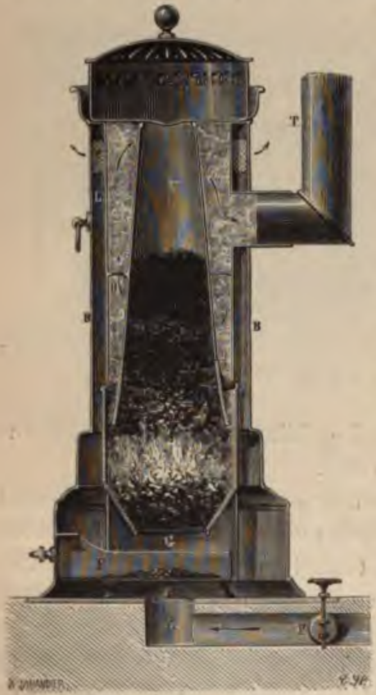


Fig. 222.—Ventilating Stove.

The stove represented in Fig. 222[1] belongs to the class of what are called in France *calorifères*, and in England *ventilating stoves*, being constructed with a view to promoting the circulation and renewal of the air of the apartment. G is the fire-box, over which is the feeder U, containing unburned fuel, and tightly closed at top by a lid, which is removed only when fresh fuel is to be introduced. The ash-pan F has a door pierced with holes for admitting air to support combustion. The flame and smoke issue at the edge of the fire-box, and after circulating round the chamber O which surrounds the feeder, enter the pipe T which leads to the chimney. The chamber O is surrounded by another inclosure L, through which fresh air passes, entering below at A, and escaping into the room through perforations in the upper part of the stove as indicated by the arrows. The amount of fresh air thus admitted can be regulated by the throttle-valve P.

---

[1] With the exception of the ventilating arrangement, this stove is identical with what is known in this country as Walker's self-feeding stove.

CHAPTER XXIV.

FUSION AND SOLIDIFICATION.

225. Fusion.—Many solid bodies, when raised to a sufficiently high temperature, become liquid. This change of state is called *melting* or *fusion*, and the temperature at which it occurs (called the melting-point, or temperature of fusion) is constant for each substance, with the exception of the variations—which in ordinary circumstances are insignificant—due to differences of pressure (§ 237). The melting-points of several substances are given in the following table:—

TABLE OF MELTING-POINTS, IN DEGREES CENTIGRADE.

Mercury,	−39	Tin,	230
Ice,	0	Bismuth,	562
Butter,	33	Lead,	320
Lard,	33	Zinc,	360
Spermaceti,	49	Antimony,	432
Stearine,	55	Bronze,	900
Yellow Wax,	62	Pure Silver,	1000
White Wax,	68	Copper,	1150
Stearic Acid,	70	Coined Gold,	1180
Phosphorus,	44	Pure Gold,	1250
Potassium,	63	Cast Iron,	1050 to 1250
Sodium,	95	Steel,	1300 to 1400
Iodine,	107	Wrought Iron,	1500 to 1600
Sulphur,	110	Platinum,	2000

Some bodies, such as charcoal, have hitherto resisted all attempts to reduce them to the liquid state; but this is to be attributed only to the insufficiency of the means which we are able to employ.

It is probable that, by proper variations of temperature and pressure, all simple substances, and all compound substances which would not be decomposed, could be compelled to assume the three forms, solid, liquid, and gaseous.

The passage from the solid to the liquid state is generally abrupt;

but this is not always the case. Glass, for instance, before reaching a state of perfect liquefaction, passes through a series of intermediate stages in which it is of a viscous consistency, and can be easily drawn out into exceedingly fine threads, or moulded into different shapes.

226. Constant Temperature during Fusion.—During the entire time of fusion the temperature remains constant. Thus if a vessel containing ice be placed on the fire, the ice will melt more quickly as the fire is hotter; but if the mixture of ice and water be constantly stirred, a thermometer placed in it will indicate the temperature zero without variation so long as any ice remains unmelted; it is only after all the ice has become liquid that a rise of temperature will be observed.

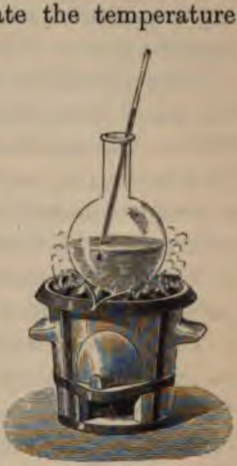


Fig. 223.—Fusion of Sulphur.

In the same way, if sulphur be heated in a glass vessel, the temperature indicated by a thermometer placed in the vessel will rise gradually until it reaches about 110°, when a portion of the sulphur will be seen to become liquid, and if the vessel be shaken during the time of fusion, until the whole of the sulphur is liquefied, the temperature will be observed to remain steadily at this point.

227. Latent Heat of Fusion. — This constancy of temperature is very remarkable, and leads to some important conclusions. In fact, as the action of the fire continues the same throughout the entire time of fusion, while the thermometer remains stationary, all the heat supplied after liquefaction has begun, *appears* to be lost. Hence we conclude, that in order that a body may pass from the solid to the liquid state, it must absorb a certain quantity of heat which produces no thermometric effect. Black, who was the first to investigate this subject, gave to the heat thus absorbed the name of *latent heat*, by which it is still usually designated. A similar absorption of heat without thermometric effect occurs when a boiling liquid is converted into vapour. Hence it is necessary to distinguish between the *latent heat of fusion* and the *latent heat of vaporization*.[1] Latent heat then may be defined as the heat absorbed in virtue of change of state from solid to liquid, or from liquid to gaseous. Modern philosophy teaches that the processes of fusion and vaporization involve the performance of work by heat in opposition to molecular force, and that an amount of heat disappears (or becomes latent) which is the exact equivalent of the work performed.

---

[1] The former is often called the latent heat of the liquid, and the latter of the vapour. Thus we speak of the latent heat of water (which becomes latent in the melting of ice), a tent heat of steam (which becomes latent in the vaporization of water).

228. Heat of Fusion of Ice.—The latent heat of fusion is different for different substances. Its amount for ice (commonly called the latent heat of water) can be approximately determined by the following experiment, which is due to Black, who was the first to make accurate observations on this subject.

Take a pound of ice at 0° C. and a pound of water at 79° C.; let the water be poured over the ice, and the mixture rapidly stirred. The ice will melt, and two pounds of water at 0° will be obtained. This interesting experiment shows that all the heat necessary to raise a pound of water from 0° to 79° has been absorbed in melting a pound of ice; and it is thus directly proved that the heat required to melt a pound of ice is exactly the same as that required to raise the temperature of a pound of water from 0° to 79°.

The name *unit of heat* is given to the amount of heat necessary to raise unit mass of water one degree. It will be different according to the unit of mass and scale of temperature adopted. The pound-centigrade unit is the heat required to raise a pound of water through one degree Centigrade, and we see from above that 79 of these units are required for the melting of a pound of ice.[1]

On comparing the heat of fusion of ice with that of some other bodies as given in the table § 348, it will be seen that its amount is notably greater for ice than for any of the other substances. Ice is in this sense the most difficult to melt, and water the most difficult to freeze of all substances, a fact which is of immense importance in the economy of nature, as tending to retard the processes both of freezing and thawing. Even as it is, the effects of a sudden thaw are often very disastrous, and yet, for every pound of ice melted, as much heat is required as would raise the water produced through 79° C. or 142° F.

229. Solution.—The reduction of a body from the solid to the liquid state may be effected by other means than by the direct action of heat; it may be produced by the action of a liquid. This is what occurs when, for instance, a grain of salt or of sugar is placed in water; the body is said to *melt* or *dissolve* in the water. Solution, like fusion, is accompanied by the disappearance of heat consequent on the change from the solid to the liquid state. For example, when nitrate of ammonia is rapidly dissolved in water, a fall of from 20° to 25° Cent. is observed.

---

[1] The statements in this paragraph, including the definition of a unit of heat, are only approximate. The subject will be resumed in Chap. xxxi.

Unlike fusion, it is attached to no definite temperature, but occurs with more or less freedom over a wide range. Rise of temperature usually favours it; but there are some strongly marked exceptions.

230. Freezing Mixtures.—The absorption of heat which accompanies the liquefaction of solids is the basis of the action of freezing mixtures. In all such mixtures there is at least one solid ingredient which, by the action of the rest, is reduced to the liquid state, thus occasioning a fall of temperature proportional to the latent heat of its liquefaction.

The mixture most commonly employed in the laboratory is one of snow and salt, in the proportion of two parts of the former to one of the latter. This mixture assumes a temperature of about −18° C. (0° F.), and furnished Fahrenheit with the zero of his scale. In this instance there is a double absorption of heat caused by the simultaneous melting of the snow and dissolving of the salt.

We may obtain a freezing mixture without the use of snow or ice. Such mixtures are often employed for the artificial freezing of water. Various kinds of apparatus have been invented for this purpose, one of which is shown in Fig. 224. It consists of a metal cylinder, containing the freezing mixture (hydrochloric acid and sulphate of soda). In the cylinder is placed a mould formed of two concentric vessels with the water between them, an arrangement which has the advantage of increasing the surface of contact. The whole is set upon a cradle, the rocking of which greatly ass [illegible] operation. We sub-

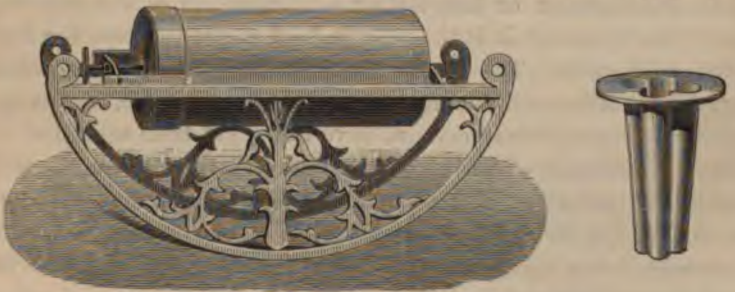


Fig. 224.—Freezing Rocker.

join a table of the most important freezing mixtures, with the proportions corresponding to the maximum effect. These proportions are evidently of importance, since the amount of heat absorbed in a given time depends upon the quantity of solid matter that is reduced to the liquid state during that time. There may also be chemical action between the materials of which the mixture is composed. This is always attended with generation of heat, so that in this case the actual result depends upon the difference of two opposite effects. Thus the mixture of four parts of sulphuric acid with one of ice causes a rise of temperature of about 50° or 60°, while four parts of ice and one of sulphuric acid produce a cold of from −15° to −20° C.

TABLE.

	Proportions by Weight.	Fall of Temperature in Centigrade degrees.
Snow or Powdered Ice,	2	from 0° to − 21°.
Bay-salt,	1	
Snow,	3	from 0° to − 48°.
Crystallized Chloride of Calcium,	4	
Nitrate of Ammonia,	1	from + 10° to − 15°.
Water,	1	
Sal-ammoniac,	5	from + 10° to − 15°.
Nitrate of Potash,	5	
Sulphate of Soda,	8	
Water,	16	
Sulphate of Soda,	8	from + 10° to − 17°.
Hydrochloric Acid,	5	

231. Solidification or Congelation.—Congelation is the inverse of fusion; that is to say, it is the passage of a substance from the liquid to the solid state. The faculty of undergoing this transformation may be regarded as common to all liquids, although some, for example, alcohol and bisulphide of carbon, have never yet been solidified.

The temperature of fusion is the highest temperature at which congelation can occur, and is frequently called the *temperature of congelation* (or the *freezing-point*); but it is possible to preserve substances in the liquid state at lower temperatures. Liquids thus cooled below their so-called freezing-points have, however, if we may so say, a *tendency to freeze, which is only kept in check by the difficulty of making a commencement.* If freezing once begins, or if ever so small a piece of the same substance in the frozen state be allowed to come in contact with the liquid, congelation will quickly extend until there is none of the liquid left at a temperature below that of fusion. The condition of a liquid cooled below its freezing-point has been aptly compared to that of a row of bricks set on end in such a manner that if the first be overturned, it will cause all the rest to fall, each one overturning its successor.

The contact of its own solid infallibly produces congelation in a liquid in this condition, and the same effect may often be produced by the contact of some other solid, especially of a crystal, or by giving a slight jar to the containing vessel.

Despretz has cooled water to −20° C. in fine capillary tubes, without freezing, and Dufour has obtained a similar result by suspending globules of water in a liquid of the same specific gravity with which it would not mix.

232. Heat set free in Congelation.—At the moment when congelation takes place, the thermometer immediately rises to the temperature of the melting-point. This may be easily shown by experiment. A small glass vessel is taken, containing water, in which a mercurial thermometer is plunged. By means of a frigorific mixture the temperature is easily lowered to −10° or −12°, without the water freezing; a slight shock is then given to the glass, congelation takes place, and the mercury rises to 0°.

The heat thus produced is the equivalent of the work done by the molecular forces of the body in the passage from the liquid to the solid state. The quantity of heat thus arising is evidently the same as that which disappears in fusion, since they are the equivalents of the same amount of work performed in opposite directions. The production of this heat may be experimentally shown in another way. If we heat a quantity of lead to its melting-point (320°), and when the metal is just beginning to melt, plunge it into water, a certain rise of temperature will be observed. If we repeat the same experiment, allowing the lead time to melt completely, the temperature being still 320°, a much more considerable increase in the temperature of the water will be produced, the reason being that the lead in solidifying in contact with the water gives out its latent heat.

233. Crystallization.—When the passage from the liquid to the solid state is a gradual one, it frequently happens that the molecules group themselves in such a manner as to present regular geometric forms. This process is called crystallization, and the regular bodies thus formed are called crystals. The particular crystalline form assumed depends upon the substance, and often affords a means of recognizing it. The forms, therefore, in which bodies crystallize are among their most important characteristics, and are to some extent analogous to the shapes of animals and plants in the organic world.

In order to make a body crystallize in solidifying, the following method is employed. Suppose the given body to be bismuth; the first step is to melt it, and then leave it to itself for a time. The metal naturally begins to solidify first at the surface and at the sides, where it is most directly exposed to cooling influences from without; accordingly, when the outer layer of the metal is solidified, the interior is still in the liquid state. If the upper crust be now removed, and the liquid bismuth poured off, the sides of the vessel will be seen to be covered with a number of beautiful crystals.

If the metal were allowed to stand too long, the entire mass would become solid, the different crystals would unite, and no regularity of structure would be observable. This is the case with a great number of solids; ice is one very remarkable instance.

234. Flowers of Ice.—The tendency of ice to assume a crystalline form is seen in the fern-leaf patterns which appear on the windows in winter, caused by the congealing of moisture on them, and still more distinctly in the symmetrical forms of snow-flakes (see Chap. xxviii.) In a block of ice, however, this crystalline structure does not show itself, owing to the closeness with which the crystals fit into each other, so that a mass of this substance appears almost completely *amorphous*. Tyndall, however, in a very interesting experiment, has succeeded in gradually *decrystallizing* ice, if we may use the expression, and thus exhibiting the crystalline elements of which it is composed. The experiment consists in causing a pencil of solar rays to fall perpendicular to the surfaces of congelation on a sheet of ice, such as is naturally formed upon the surface of water in winter. A lens placed behind the ice (Fig. 225) serves to project upon a screen

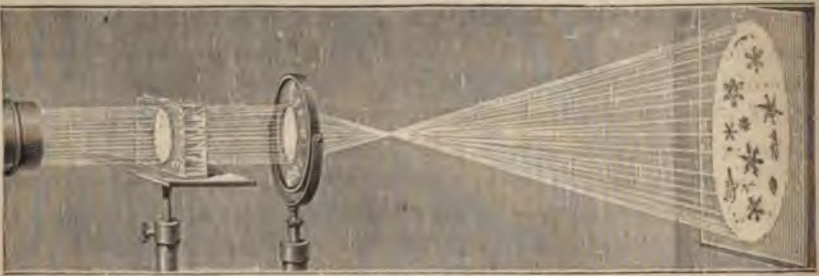


Fig. 225.—Flowers of Ice projected on a Screen.

the image of what is found in the interior of the block. The successive appearances observed upon the screen are shown in Fig. 226. A small luminous circle is first seen, from which branch out rays, resembling the petals of a flower whose pistil is the circle. Frequent changes also occur in the shape of the branches themselves, which are often cut so as to resemble fern-leaves, like those seen upon the windows during frost. In this experiment the solar heat, instead of uniformly melting the mass of ice, which it would certainly do if the mass were amorphous, acts successively upon the different crystals of which it is built up, affecting them in the reverse order of their formation. There are thus produced a number of spaces of regular shape, containing water, and producing comparatively dark images upon the screen. In the centre of each there is generally a bright spot, which corresponds to an empty space, depending on the fact that the water occupies a smaller volume than the ice from which it has been produced.

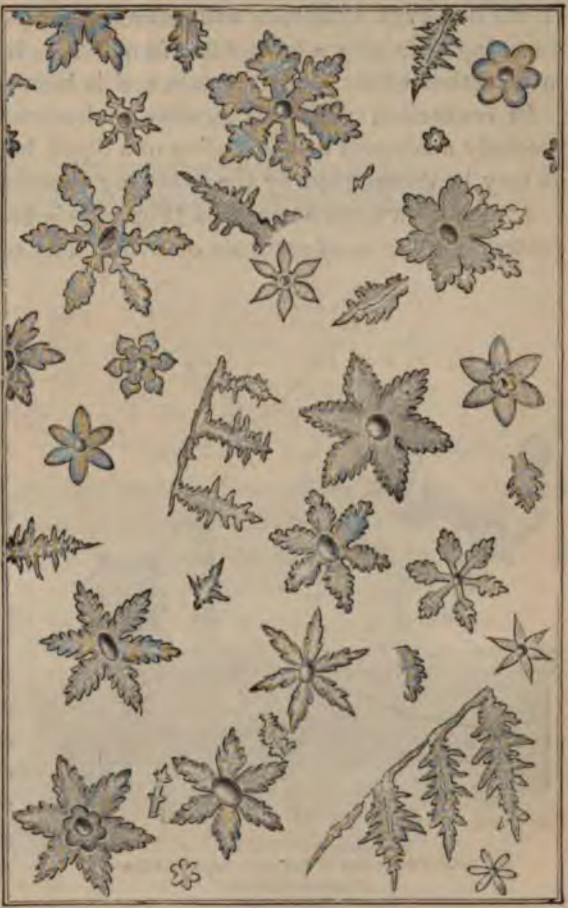


Fig. 226.—Flowers of Ice.

235. Supersaturation.—The proportion of solid matter which a liquid can hold in solution varies according to the temperature; as a general rule, though not by any means in all cases, it increases as the temperature rises. Hence it follows, that if a saturated solution be left to itself, the effect of evaporation or cooling will be gradually to diminish the quantity of matter which can be held in solution. A portion of the dissolved substance will accordingly pass into the solid state, assuming generally a crystalline form. This is an exceedingly common method of obtaining crystals, and is known as the *humid way*.

In connection with this process a phenomenon occurs which is precisely analogous to the cooling of a liquid below its freezing-point. It may be exemplified by the following experiment.

A tube drawn out at one end (Fig. 227) is filled with a warm concentrated solution of sulphate of soda. The solution is boiled, and while ebullition is proceeding freely, the tube is hermetically sealed; by this means the tube is exhausted of air. The solution when left to itself cools without the solid being precipitated, although the liquid is *supersaturated*. But if the end of the tube be broken off, and the air allowed to enter, crystallization immediately commences at the surface, and is quickly propagated through the whole length of the tube; at the same time, as we should expect, a considerable rise of temperature is observed. If the phenomenon does not at once occur on the admission of the air, it can be produced with certainty by throwing a small piece of the solid sulphate into the solution.

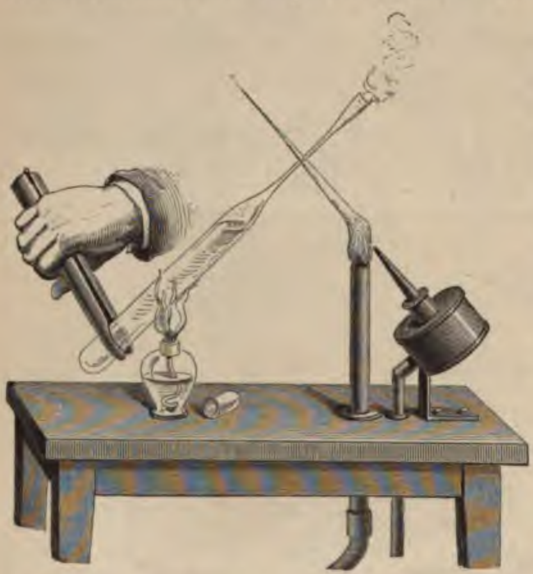


Fig. 227.—Preparation of Supersaturated Solution of Sulphate of Soda.

236. Change of Volume at the Moment of Congelation. Expansive Force of Ice.—In passing from the liquid to the solid state, bodies generally undergo a diminution of volume; there are, however, exceptions, such as ice, bismuth, silver, and cast-iron. It is this property which renders this latter substance so well adapted for the purposes of moulding, as it enables the metal to penetrate completely into every part of the mould. The expansion of ice is considerable, amounting to about $\frac{1}{14}$; its production is attended by enormous mechanical force, just as in the analogous case of expansion by heat.

Its effect in bursting water-pipes is well known. The following experiment illustrates this expansive force. A tube of forged iron (Fig. 228) is filled with water, and tightly closed by a screw-stopper. The tube is then surrounded with a freezing mixture of snow and salt. After some time the water congeals, a loud report is often heard, and the tube is found to be rent.

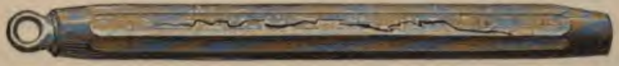


Fig. 228.—Bursting of Iron Tube by Expansion of Water in Freezing.

The following experiment, performed by Major Williams at Quebec, is still more striking. He filled a 12-inch shell with water and closed it with a wooden stopper, driven in with a mallet. The shell was then exposed to the air, the temperature being −28° C. (−18° F.) The water froze, and the bung was projected to a distance of more than 100 yards, while a cylinder of ice of about 8 inches in length was protruded from the hole. In another experiment the shell split in halves, and a sheet of ice issued from the rent (Fig. 229).

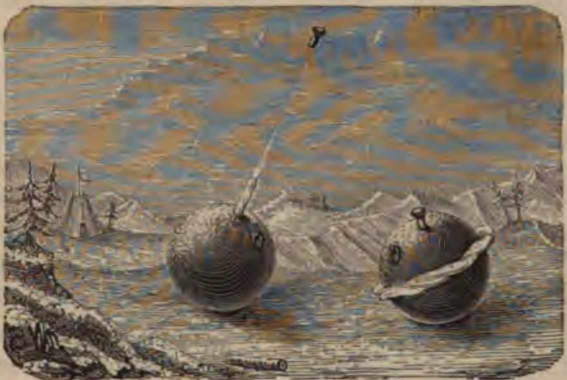
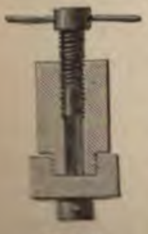


Fig. 229.—Experiment of Major Williams.

It is the expansion and consequent lightness of ice which enables it to float upon the surface of water, and thus afford a protection to animal life below.

237. Effect of Pressure on the Melting-point.—Professor James Thomson was led by theoretical considerations to the conclusion that, in the case of a substance which, like water, expands in solidifying, the freezing (or melting) point must of necessity be lowered by pressure, and that a mixture of ice and ice-cold water would fall in temperature on the application of pressure. His reasoning[1] consisted in showing that it would otherwise be possible (theoretically at least) to construct a machine which should be a perpetual source of work without supply; that is, what is commonly called a perpetual motion.

The matter was shortly afterwards put to the test of experiment by Professor (now Sir) W. Thomson, who compressed, in an Œrsted's piezometer, a mixture of ice and water, in which was inserted a very delicate thermometer protected from pressure in the same manner as the instrument represented in Fig. 194c (§189). The thermometer showed a regular fall of temperature as pressure was applied, followed by a return to 0° C. on removing the pressure. Pressures of 8·1 and 16·8 atmospheres (in excess of atmospheric pressure) lowered the freezing-point by ·106 and ·232 of a degree Fahr. respectively as indicated by the thermometer, results which agree almost exactly with Prof. J. Thomson's prediction of ·0075 of a degree Cent., or ·0135 of a degree Fahr. per atmosphere.


[illegible]

Mousson has since succeeded in reducing the melting-point several degrees by means of enormous pressure. He employed two forms of apparatus, by the first of which he melted ice at the temperature of −5° C., and kept the water thus produced for a considerable time at this temperature. This apparatus had windows (consisting of blocks of glass) in its sides, through which the melting of the ice was seen. His second form of apparatus, which bore a general resemblance to the first, is represented in the annexed figure. It consisted of a steel prism with a cylindrical bore, having one of its extremities closed by a conical stopper strongly screwed in, the rest of the bore being traversed by a screw-piston of steel. The apparatus [illegible] inverted, and nearly filled with water recently boiled, into which [illegible] copper was dropped, to serve as an index. The apparatus, still remaining in the inverted position, was surrounded by a freezing mixture, by means of which the water was reduced to ice at the temperature of −18° C. The stopper was then screwed into its place, and the apparatus placed in the erect position. The piston was then screwed down upon the ice with great force, the pressure exerted being estimated in some of the experiments at several thousand atmospheres. The pressure was then relaxed, and, on removing the stopper, the copper index was found to have fallen to the bottom of the bore, showing that the ice had been liquefied.

---

[1] [illegible] Society, *Edinburgh.* January, 1849.—*Cambridge and Dublin* [illegible], 1850.

Experiments conducted by Bunsen and Hopkins have shown that wax, spermaceti, sulphur, stearin, and paraffin—substances which, unlike ice, expand in melting—have their melting points *raised* by pressure, a result which had been predicted by Professor W. Thomson.

237A. Effect of Stress in general upon Melting and Solution.—In the experiments above described, the pressure applied was hydrostatical, and was therefore equal in all directions. But a solid may be exposed to pressure in one direction only, or to pull in one or more directions, or it may be subjected to shearing, twisting, or bending forces, all these being included under the general name of *stress*.

Reasoning, based on the general laws of energy, leads to the conclusion that stress of any kind other than hydrostatic, applied to a solid, must lower its melting-point. To quote Professor J. Thomson (*Proc. Roy. Soc.* Dec. 1861), "Any stresses whatever, tending to change the form of a piece of ice in ice-cold water, must impart to the ice a tendency to melt away, and to give out its cold, which will tend to generate, from the surrounding water, an equivalent quantity of ice free from the applied stresses," and "stresses tending to change the form of any crystals in the saturated solutions from which they have been crystallized must give them a tendency to dissolve away, and to generate, in substitution for themselves, other crystals free from the applied stresses or any equivalent stresses."[1] This conclusion he verified by experiments on crystals of common salt. He at the same time suggested, as an important subject for investigation, the effect of hydrostatic pressure on the crystallization of solutions, a subject which was afterwards taken up experimentally by Sorby, who obtained effects analogous to those above indicated as occurring in connection with the melting of ice and wax.

---

[1] Professor Thomson draws these inferences from the following principle, which he assumes (we think justly) as a physical axiom:—If any substance or system of substances be in a condition in which it is free to change its state [as ice, for example, in contact with water at 0° C., is free to melt], and if mechanical work be applied to it as potential energy in such a way that the occurrence of the change of state will make it lose that mechanical work from the condition of potential energy, without receiving other potential energy as an equivalent; *then the substance or system will pass into the changed state.*

238. Regelation of Ice.—Faraday in 1850 called attention to the fact that pieces of moist ice placed in contact with one another will freeze together even in a warm atmosphere. This phenomenon, to which Tyndall has given the name of *regelation*, admits of ready explanation by the principles just enunciated. Capillary action at the boundaries of the film of water which connects the pieces placed in contact, produces an effect equivalent to attraction between them, just as two plates of clean glass with a film of water between them seem to adhere. Ice being wetted by water, the boundary of the connecting film is concave, and this concavity implies a diminution of pressure in the interior. The film, therefore, exerts upon the ice a pressure less than atmospheric; and as the remote sides of the blocks are exposed to atmospheric pressure, there is a resultant force urging them together and producing stress at the small surface of contact. Melting of the ice therefore occurs at the places of contact, and the cold thus evolved freezes the adjacent portions of the water film, which, being at less than atmospheric pressure, will begin to freeze at a temperature a little above the ordinary freezing-point.

As regards the amount of the force urging the pieces together, if two flat pieces of ice be supported with their faces vertical, and if they be united by a film from whose lower edge water trickles away, the hydrostatic pressure at any point within this film is less than atmospheric by an amount represented, in weight of water, by the height of this point above the part from which water trickles. If, for simplicity, we suppose the film circular, the plates will be pressed together with a force equal to the weight of a cylinder of water whose base is the film and whose height is the radius.

239. Apparent Plasticity of Ice. Motion of Glaciers.—A glacier may be described in general terms as a mass of ice deriving its origin from mountain snows, and extending from the snow-fields along channels in the mountain sides to the valleys beneath.

The first accurate observations on the movements of glaciers were made in 1842 by the late Professor (afterwards Principal) J. D. Forbes, who established the fact that glaciers descend along their beds with a motion resembling that of a pailful of mortar poured down a sloping trough; the surface moving faster than the bottom and the centre faster than the sides. He summed up his view by saying, "A glacier is an imperfect fluid, or a viscous body which is urged down slopes of a certain inclination by the mutual pressure of its parts."

This apparent viscosity is explained by the principles of § 237A. According to these principles the ice should melt away at the places where stress is most severe, an equivalent quantity of ice being formed elsewhere. The ice would thus gradually yield to the applied forces, and might be moulded into new forms, without undergoing rupture. Breaches of continuity might be produced in places where the stress consisted mainly of a pull, for the pull would lower the freezing-point, and thus indirectly as well as directly tend to produce ruptures, in the form of fissures transverse to the direction of most intense pull. The effect of violent compression in any direction would, on the other hand, be, not to crack the ice, but to melt a portion of its interior sufficient to relieve the pressure in the particular part affected, and to transfer the excess of material to neighbouring parts, which must in their turn give way in the same gradual manner.

In connection with this explanation it is to be observed that the temperature of a glacier is always about 0° C., and that its structure is eminently porous and permeated with ice-cold water. These are conditions eminently favourable (the former, but not the latter, being essential) to the production of changes of form depending on the lowering of the melting-point by stresses.

This explanation is due to Professor J. Thomson[1] (*British Association Report,* 1857). Professor Tyndall had previously attempted to account for the phenomena of glacier motion by supposing that the ice is fractured by the forces to which it is subjected, and that the broken pieces, after being pushed into their new positions, are united by regelation. In support of this view he performed several very interesting and novel experiments on the moulding of ice by pressure, such as striking medals of ice with a die, and producing a clear transparent cake of ice by powerfully compressing broken pieces in a boxwood mould (Fig. 231).

Interesting experiments on the plasticity of ice may be performed by filling an iron shell with water and placing it in a freezing mixture, leaving the aperture open. As the water freezes, a cylinder of ice will be gradually protruded. This experiment is due to Mr. Christie. Professor Forbes obtained a similar result by using a very strong glass jar; and by smearing the interior, just below the neck, with colouring matter, he demonstrated that the external layer of ice which was first formed, slid along the glass as the freezing proceeded, until it was at length protruded beyond the mouth.

---

[1] If it should be objected that the lowering of the melting-point by stress is too insignificant to produce the vast effects here attributed to it, the answer is that, when ice and water are present together, the slightest difference is sufficient to determine which portion of the water shall freeze, or which portion of the ice shall melt. In default of a more powerful cause, those portions of ice which are most stressed will melt first.

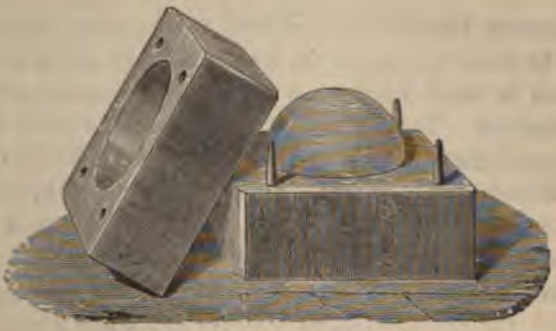


Fig. 231.—Ice Moulded by Pressure.

In the experiments of Major Williams, described in § 236, it is probable that much of the water remained unfrozen until its pressure was relieved by the bursting of the shells.

CHAPTER XXV.

EVAPORATION.

240. Transformation into the State of Vapour.—The majority of liquids, when left to themselves in contact with the atmosphere, gradually pass into the state of vapour and disappear. This phenomenon occurs much more rapidly with some liquids than with others, and those which evaporate most readily are said to be the most volatile. Thus, if a drop of ether be let fall upon any substance, it disappears almost instantaneously; alcohol also evaporates very quickly, but water requires a much longer time for a similar transformation. The change is in all cases accelerated by an increase of temperature; in fact, when we *dry* a body before the fire, we are simply availing ourselves of this property of heat to hasten the evaporation of the moisture of the body. Evaporation may also take place from solids. Thus camphor, iodine, and several other substances pass directly from the solid to the gaseous state, and we shall see hereafter that the vapour of ice can be detected at temperatures far below the freezing-point.

Evaporation, unlike fusion, occurs over a very wide range of temperature. There appears, however, to be a temperature for each substance, below which evaporation, if it exist at all, cannot be detected. This is the case with mercury at 0° C., and with sulphuric acid at ordinary atmospheric temperatures.

241. Vapour, Gas.—The words *gas* and *vapour* have no essential difference of meaning. A vapour is the gas into which a liquid is changed by evaporation. Every gas is probably the vapour of a certain liquid. The word vapour is especially applied to the gaseous condition of bodies which are usually met with in the liquid or solid state, as water, sulphur, &c.; while the word gas generally denotes a body which, under ordinary conditions, is never found in any state taken to expel any bubbles of air which may have remained adhering to the mercury. The tube is then inverted in the deep bowl MN, when the ether ascends to the surface of the mercury, is there converted into vapour, and produces a sensible depression of the mercurial column. If the quantity of ether be sufficiently small, and if the tube be kept sufficiently high, no liquid will be perceived in the space above the mercury; this space, in fact, is not saturated. The tension of the vapour which occupies it is given by the difference between the height of the column in the tube and of a barometer placed beside it. If the tube be gradually lowered, this difference will at first be seen to increase, that is, the tension of the vapour of ether increases; but if we continue the process, a portion of liquid ether will be observed to collect above the mercury, and after this, if we lower the tube any further, the height of the mercury in it remains invariable. The only effect is to increase the quantity of liquid deposited from the vapour.[1]

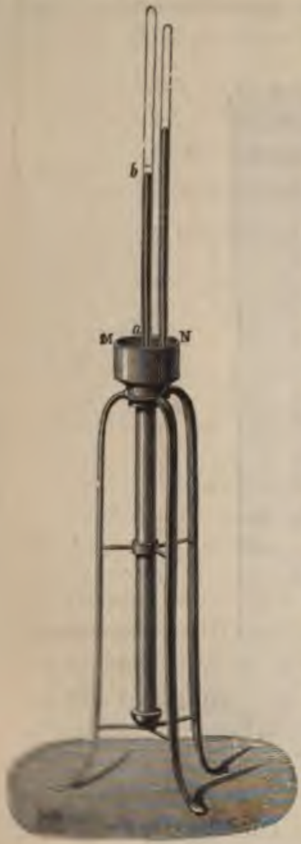


Fig. 233.—Maximum Tension of Vapours.

243. Influence of Temperature on the Maximum Tension.—Returning now to the apparatus represented in Fig. 232, suppose that some of the liquid remains unevaporated in the bottom of the globe, and let the globe be subjected to an increase of temperature. An increase of elastic force will at once be indicated by the manometer, while the quantity of liquid will be diminished. The maximum tension of a vapour, therefore, and also its maximum density, increase with the temperature; and consequently, in order to saturate a given space, a quantity of vapour is required which increases with the temperature. In a subsequent chapter we shall give the results of experiments on the maximum tension of aqueous vapour at different temperatures, and it will be seen that the increase is exceedingly rapid.

---

[1] Strictly speaking, there will be a slight additional depression of the mercurial column due to the weight of the liquid thus deposited on its summit; but this effect will generally be very small, as the vapour occupies much more space than the liquid which it yields.

Fig. 234 is a graphical representation of the rate at which the maximum density of a vapour increases with the temperature. Lengths are laid off on the base-line AB, to represent temperatures from −20° to +35° C., and ordinates are erected at every fifth degree, proportional to the weights of vapour required to saturate the same space at different temperatures. The curve CD, drawn through the extremities of these ordinates, is the curve of vapour-density as a function of temperature. The figures on the right hand indicate the number of grammes of vapour required to saturate a cubic metre.

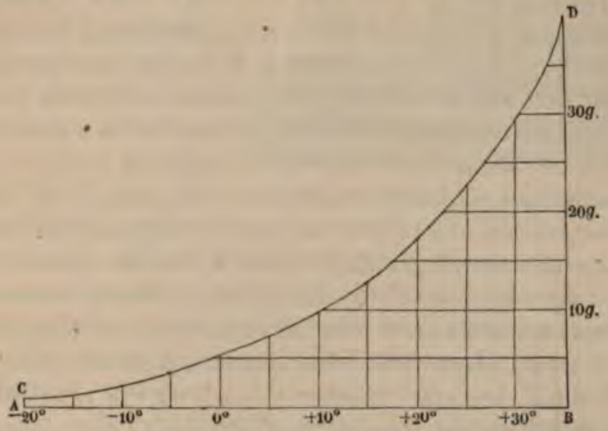


Fig. 234.—Saturation at different Temperatures.

244. Mixture of Gas and Vapour.—The experiments with the apparatus of Fig. 232 may be repeated after filling the globe with dry air, or any other dry gas, and the results finally obtained will be the same as with the exhausted globe. If, as before, we introduce successive small quantities of a liquid, it will be converted into vapour, and the pressure will go on increasing till saturation is attained; the elastic force of vapour will then be found to be exactly the same as in the case of the vacuous globe, and the quantity of liquid evaporated will also be the same.

There is, however, one important difference. In the vacuum the complete evaporation of the liquid is almost instantaneous; in a gas, on the other hand, the evaporation and consequent increase of pressure proceed with comparative slowness; and the difference between the two cases is more marked in proportion as the pressure of the gas is greater.

We may lay down, then, the two following laws for the mixture of a vapour with a gas:—

1. *The weight of vapour which will enter a given space is the same whether this space be empty or filled with gas, provided plenty of time be allowed.*

2. *When a gas is saturated with vapour, the actual tension of the mixture is the sum of the tensions due to the gas and vapour separately; that is to say, it is equal to the pressure which the gas would exert if it alone occupied the whole space, plus the maximum tension of vapour for the temperature of the mixture.*

This second law evidently comes under the general rule for determining the pressure of a mixture of gases (§ 127); and the same rule applies to a mixture of gas and vapour when the quantity of the latter *falls short of* saturation. Each element in a mixture of gases and vapours exerts the same pressure on the walls of the containing vessel as it would exert if the other elements were removed.

It is doubtful, however, whether these laws are rigorously true. It would rather appear from some of Regnault's experiments, that the quantity of vapour taken up in a given space is slightly, though almost insensibly, diminished, as the density of the gas which occupies the space is increased.

245. Liquefaction of Gases.—When vapour exists in the state of saturation, any diminution in the volume must, if the temperature is preserved constant, involve the liquefaction of as much of the vapour as would occupy the difference of volumes; and the vapour which remains will still be at the original density and tension. A vapour existing by itself may therefore be completely liquefied by subjecting it to a pressure exceeding, by ever so slight an amount, the maximum tension corresponding to the temperature, provided that the containing vessel is prevented from rising in temperature.

Again, if a vapour at saturation be subjected to a fall of temperature, while its volume remains unchanged, a portion of it must be liquefied corresponding to the difference between the density of saturation at the higher and at the lower temperature. This operation will obviously diminish the tension, since this will now be the maximum tension corresponding to the lower instead of to the higher temperature.

There are therefore two distinct means of liquefying a vapour—

increase of pressure, and lowering of temperature. They are employed sometimes separately, and sometimes in conjunction.

Fig. 235 represents the apparatus usually employed for obtaining sulphurous acid in the liquid state. The gas, which is generated in a glass globe, passes first into a washing-bottle, then through a drying-tube, and finally into a tube surrounded with a freezing mixture of snow and salt.

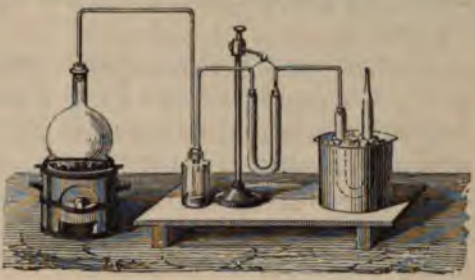


Fig. 235.—Liquefaction of Sulphurous Acid.

Pouillet's apparatus, described in § 120, serves to liquefy most gases by means of compression

In order to ascertain the pressures at which liquefaction takes place, or, in other words, the maximum tensions of gases, one of the tubes in that apparatus is replaced by a shorter tube, containing atmospheric air, and serving as a manometer.

By this means Pouillet has found that, at the temperature of 10°C., sulphurous acid is liquefied by a pressure of 2½ atmospheres, nitrous oxide by a pressure of 43, and carbonic acid by a pressure of 45 atmospheres.

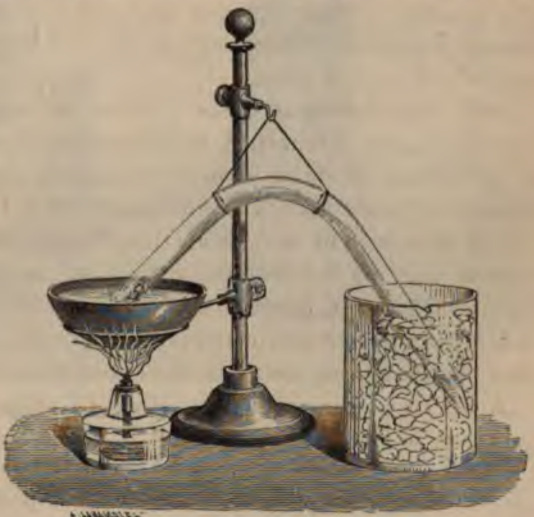


Fig. 236.—Faraday's Apparatus.

246. Faraday's Method.—Faraday, who was the first to conduct methodical experiments on the liquefaction of gases, employed, in the first instance, the simple apparatus represented in Fig. 236. It consists of a very strong bent glass tube, one end of which contains ingredients which evolve the gas on the application of heat, while the other is immersed in a freezing mixture. The pressure produced by the evolution of the gas in large quantity in a confined space, combines with the cold of the freezing mixture to produce liquefaction of the gas, and the liquid accordingly collects in the cold end of the tube.

Thilorier, about the year 1834, invented the apparatus represented in Fig. 237, which is based on this method of Faraday, and is intended for liquefying carbonic acid gas. This operation requires the enormous pressure of about fifty atmospheres at ordinary temperatures. If a slight rise of temperature occur from the chemical actions attending the production of the gas, a pressure of 75 or 80 atmospheres may not improbably be required. Hence great care is necessary in testing the strength of the metal employed in the construction of the apparatus. It was formerly made of cast iron, and strengthened by wrought-iron hoops; but the construction has since been changed on account of a terrible explosion, which cost the life of one of the operators. At present the vessels are formed of three parts; the inner one of lead, the next *e*, which completely envelops this, of copper, and finally, the hoops *ff* of wrought iron (Fig. 237), which bind the whole together. The apparatus consists of two dis-

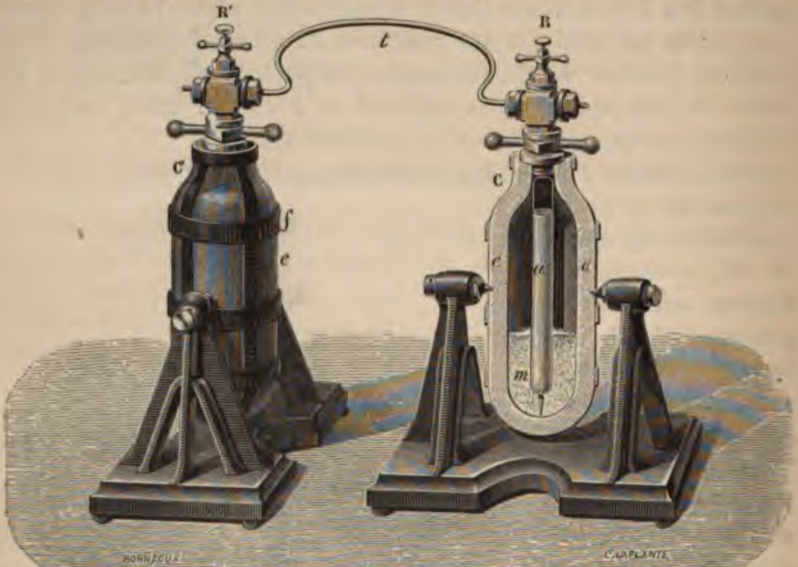


Fig. 237.—Thilorier's Apparatus.

tinct reservoirs. In the generator C is placed bicarbonate of soda, and a vertical tube a, open at top, containing sulphuric acid. By imparting an oscillatory movement to the vessel about the two pivots which support it near the middle, the sulphuric acid is gradually spilt, and the carbonic acid is evolved, and becomes liquid in the interior. The generator is then connected with the condenser C′ by the tube t, and the stop-cocks R and R′ are opened. As soon as the two vessels are in communication, the liquid carbonic acid passes into the condenser, which is at a lower temperature than the generator, and represents the cold branch of Faraday's apparatus. The generator can then be disconnected and recharged, and thus several pints of liquid carbonic acid may be obtained.

In the foregoing methods, the pressure which produces liquefaction is furnished by the evolution of the gas itself.

In some other forms of apparatus the pressure is obtained by the use of one or more compression-pumps, which force the gas from the vessel in which it is generated into a second vessel, which is kept cool either by ice or a freezing mixture. The apparatus of this kind which is most extensively used is that devised by Bianchi. It consists of a compression-pump driven by a crank furnished with a fly-wheel, and turned by hand.

Faraday, in his later experiments, employed two pumps, the first having a piston of an inch, and the second of only half an inch diameter. The first pump in the earlier stage of the operation forced the gas through the second into the receiver. In the later stage the second pump was also worked, so as to force the gas already condensed to 10, 15, or 20 atmospheres into the receiver at a much higher pressure. The receiver was a tube of green bottle-glass, and was immersed in a very intense freezing mixture, consisting of solid carbonic acid and ether, the cooling effect being sometimes increased by exhausting the air and vapour from the vessel containing the freezing mixture, so as to promote more rapid evaporation.

246 A. Continuity of the Liquid and Gaseous States.—Remarkable results were obtained by Cagniard de la Tour[1] by heating volatile liquids (alcohol, petroleum, and sulphuric ether) in closed tubes of great strength, and of capacity about double the volume of the inclosed liquid. At certain temperatures (36° C. for alcohol, and 42° for ether) the liquid suddenly disappeared, becoming apparently converted into vapour.

---

[1] *Ann. de Chim.* II. xxi.

Drion,[1] by similar experiments upon hydrochloric ether, hyponitric acid, and sulphurous acid, showed—

1. That the coefficients of apparent expansion of these liquids increase rapidly with the temperature.

2. That they become equal to the coefficient of expansion of air, at temperatures much lower than those at which total conversion into vapour occurs.

3. That they may even become double and more than double the coefficient of expansion of air; for example, at 130° C. the coefficient of expansion of sulphurous acid was ·009571.

Thilorier had previously shown that the expansion of liquid carbonic acid between the temperatures 0° and 30° C. is four times as great as that of air.

Drion further observed, that when the temperature was raised very gradually to the point of total vaporization, the free surface lost its definition, and was replaced by a nebulous zone without definite edges and destitute of reflecting power. This zone increased in size both upwards and downwards, but at the same time became less visible, until the tube appeared completely empty. The same appearances were reproduced in inverse order on gradually cooling the tube.

When the liquid was contained in a capillary tube, or when a capillary tube was partly immersed in it, the curvature of the meniscus and the capillary elevation decreased as the temperature rose, until at length, just before the occurrence of total vaporization, the surface became plane, and the level was the same within as without the tube.

Dr. Andrews, by a series of elaborate experiments on carbonic acid, with the aid of an apparatus which permitted the pressure and temperature to be altered independently of each other, has shown that at temperatures above 31° C. this gas cannot be liquefied, but, when subjected to intense pressure, becomes reduced to a condition in which, though homogeneous, it is neither a liquid nor a gas. When in this condition, lowering of temperature under constant pressure will reduce it to a liquid, and diminution of pressure at constant temperature will reduce it to a gas; but in neither case can any breach of continuity be detected in the transition.

On the other hand, at temperatures below 31°, the substance remains completely gaseous until the pressure reaches a certain limit depending on the temperature, and any pressure exceeding this limit causes liquefaction to commence and to continue till the whole of the gas is liquefied, the boundary between the liquefied and unliquefied portions being always sharply defined.

---

[1] *Ann. de Chim.* III. lvi.

The temperature 31°C., or more exactly 30·92°C. (87·7°F.), may therefore be called the critical temperature for carbonic acid; and it is probable that every other substance, whether usually occurring in the gaseous or in the liquid form, has in like manner its own critical temperature. Dr. Andrews found that nitrous oxide, hydrochloric acid, ammonia, sulphuric ether, and sulphuret of carbon, all exhibited critical temperatures, which, in the case of some of these substances, were above 100°C.

It is probable that, in the experiments of Cagniard de la Tour and Drion, the so-called total conversion into vapour was really conversion into the intermediate condition.

The continuous conversion of a gas into a liquid may be effected by first compressing it at a temperature above its critical temperature, until it is reduced to the volume which it will occupy when liquefied, and then cooling it below the critical point.

The continuous conversion of a liquid into a gas may be obtained by first raising it above the critical temperature while kept under pressure sufficient to prevent ebullition, and afterwards allowing it to expand.

When a substance is a little above its critical temperature, and occupies a volume which would, at a lower temperature, be compatible with partial liquefaction, very great changes of volume are produced by very slight changes of pressure.

On the other hand, when a substance is at a temperature a little below its critical point, and is partially liquefied, a slight increase of temperature leads to a gradual obliteration of the surface of demarcation between the liquid and the gas; and when the whole has thus been reduced to a homogeneous fluid, it can be made to exhibit an appearance of moving or flickering striæ throughout its entire mass by slightly lowering the temperature, or suddenly diminishing the pressure.

The apparatus employed in these remarkable experiments, which are described in the Bakerian Lecture (*Phil. Trans.* 1869), is shown in Fig. 237A, where *cc* are two capillary glass tubes of great strength, one of them containing the carbonic acid or other gas to be experimented on, the other containing air to serve as a manometer. These are connected with strong copper tubes *dd*, of larger diameter, containing water, and communicating with each other through ab, the water being separated from the gases by a column of mercury occupying the lower portion of each capillary tube. The steel screws ss are the instruments for applying pressure. By screwing either of them forward into the water, the contents of both tubes are compressed, and the only use of having two is to give a wider range of compression. A rectangular brass case (not shown in the figure), closed before and behind with plate-glass, surrounds each capillary tube, and allows it to be maintained at any required temperature by the flow of a stream of water.

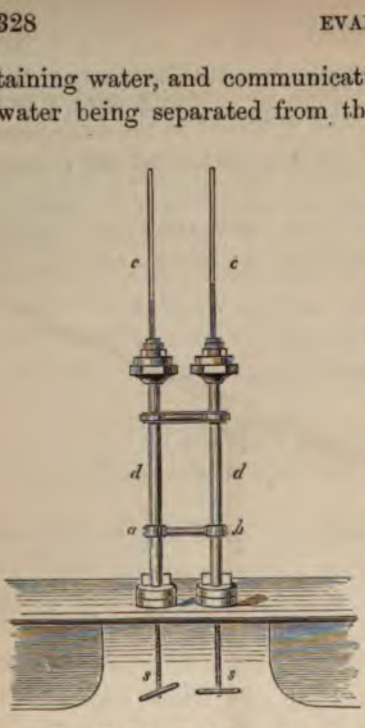


Fig. 237 A.—Andrews' Apparatus.

247. Latent Heat of Vaporization. Cold produced by Evaporation.—The passage from the liquid to the gaseous state is accompanied by the disappearance of a large quantity of heat. Whenever a liquid evaporates without the application of heat, a depression of temperature occurs. Thus, for instance, if any portion of the skin be kept moist with alcohol or ether, a decided sensation of cold is felt. Water produces the same effect in a smaller degree, because it evaporates less rapidly.

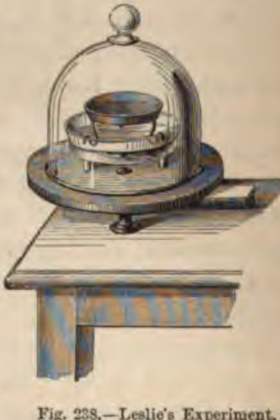


Fig. 238.—Leslie's Experiment.

The heat which thus disappears in virtue of the passage of a liquid into the gaseous condition, is called the *latent heat of vaporization*. Its amount varies according to the temperature at which the change is effected, and it is exactly restored when the vapour returns to the liquid form, provided that both changes have been effected at the same temperature. Its amount for vapour of water at the temperature 100° C. is 536°; that is to say, the quantity of heat which disappears in the evaporation of a pound of water at this temperature, and which reappears in the condensation of a pound of steam at the same temperature, would be sufficient to raise the temperature of 536 pounds of water from 0° to 1°.

The latent heat of vaporization plays an important part in the heating of buildings by steam. A pound of steam at 100°, in becoming reduced to water at 30°, gives out as much heat as about $8\frac{2}{3}$ lbs. of water at 100° in cooling down to the same temperature.

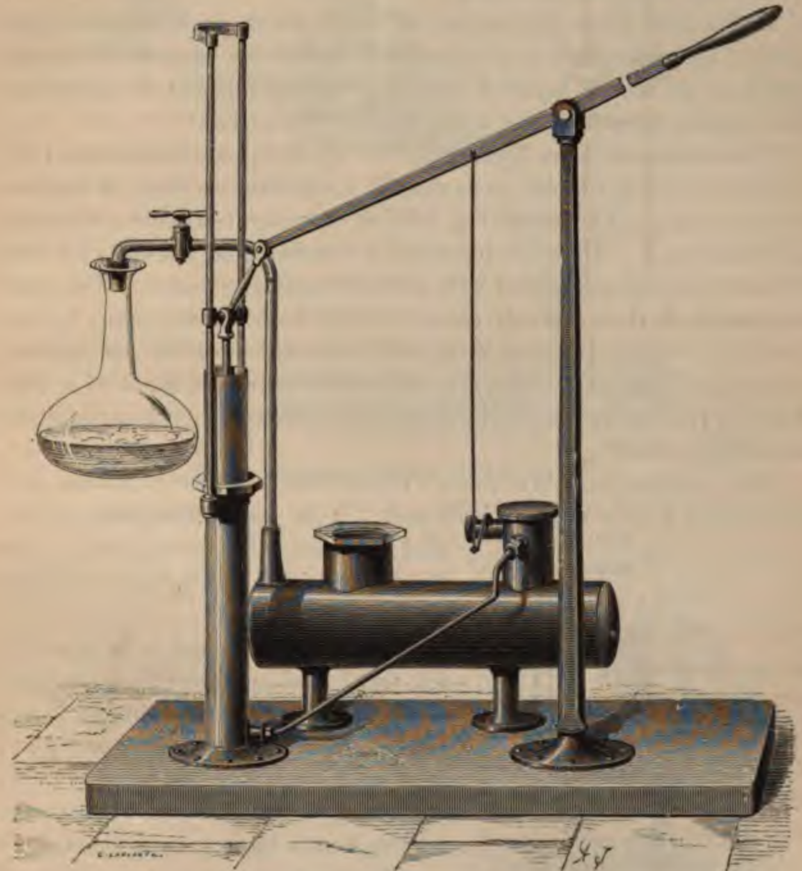


Fig. 239.—Carré's Apparatus.

248. Leslie's Experiment.—Water can be easily frozen by the cold resulting from its own evaporation, as was first shown by Leslie in a celebrated experiment. A small capsule (Fig. 238) of copper is taken, containing a little water, and is placed above a vessel containing strong sulphuric acid. The whole is placed under the receiver of an air-pump, which is then exhausted. The water evaporates with great rapidity, the vapour being absorbed by the sulphuric acid as fast as it is formed, and ice soon begins to appear on the surface. The experiment is, however, rather difficult to perform successfully. This arises from various causes.

In the first place, the vapour of water which occupies the upper part of the receiver is only imperfectly absorbed; and, in the second place, as the upper layer of the acid becomes diluted by absorbing the vapour, its affinity for water rapidly diminishes.

These obstacles have been removed by an apparatus invented by M. Carré, which enables us to obtain a considerable mass of ice in a few minutes. It consists (Fig. 239) of a leaden reservoir containing sulphuric acid. At one extremity is a vertical tube, the end of which is bent over and connected with a flask containing water. The other extremity of the reservoir communicates with an air-pump, to the handle of which is fitted a metallic rod, which drives an agitator immersed in the acid. By this means the surface of the acid is continually renewed, absorption takes place with regularity, and the water is rapidly frozen.

249. Cryophorus.—Wollaston's cryophorus (Fig. 240) consists of a bent tube with a bulb at each end. It is partly filled with water, and hermetically sealed while the liquid is in ebullition, thus expelling the air.

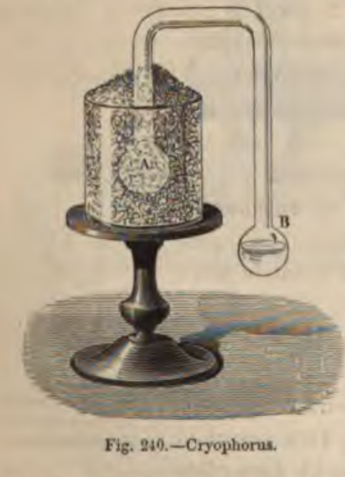


Fig. 240.—Cryophorus.

When an experiment is to be made, all the liquid is passed into the bulb B, and the bulb A is plunged into a freezing mixture, or into pounded ice. The cold condenses the vapour in A, and thus produces rapid evaporation of the water in B. In a short time needles of ice appear on the surface of the liquid.

250. Freezing of Water by the Evaporation of Ether.—Water is poured into a glass tube dipped into ether, which is contained in a glass vessel for the purpose (Fig. 241). By means of a pair of bellows a current of air is made to pass through the ether; evaporation is quickly produced, and at the end of a few minutes the water in the tube is frozen.

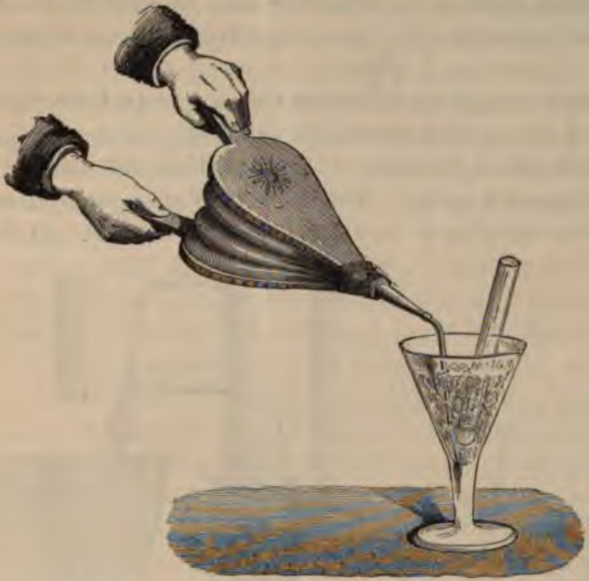


Fig. 241.—Freezing of Water by Evaporation of Ether.

If, instead of promoting evaporation of the ether by means of a current of air, the vessel were placed under the exhausted receiver of an air-pump, a much greater fall of temperature would be obtained, and even mercury might easily be frozen. This experiment, however, is injurious to the pump, owing to the solvent action of the ether on the oil with which the valves and other moving parts are lubricated.

251. Freezing of Mercury by means of Sulphurous Acid.—Mercury may be frozen by means of liquid sulphurous acid, which is much more volatile than ether. In order to escape the suffocating action of the gas, the experiment is performed in the following manner:—

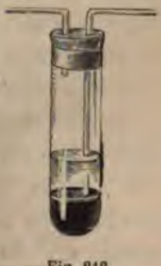


Fig. 242.
Freezing of Mercury by Evaporation of Sulphurous Acid.

Into a glass vessel (Fig. 242) are poured successively mercury and liquid sulphurous acid. The vessel is closed by an india-rubber stopper, in which two glass tubes are fitted. One of these dips to the bottom of the sulphurous acid, and is connected at its outer end with a bladder full of air. Air is passed through the liquid by compressing the bladder, and escapes, charged with vapour, through the second opening, which is fitted with an india-rubber tube leading to the open air. Evaporation proceeds with great rapidity, and the mercury soon freezes.

252. Carré's Apparatus.—The apparatus invented some years ago by M. Carré for making ice is another instance of the application of cold produced by evaporation. It consists (Figs. 243 and 244) of two parts, a boiler and a cooler. The boiler is of wrought iron, and is so constructed as to give a very large heating surface. It is three-quarters filled with a saturated solution of ammonia, which contains from six to seven hundred times its volume of gas. The cooler is of an annular form, and in the central space is placed a vessel containing the water to be frozen. In the sides of the cooler are a number of small cells, the object of which is to increase the surface of contact of the metal with the liquid.

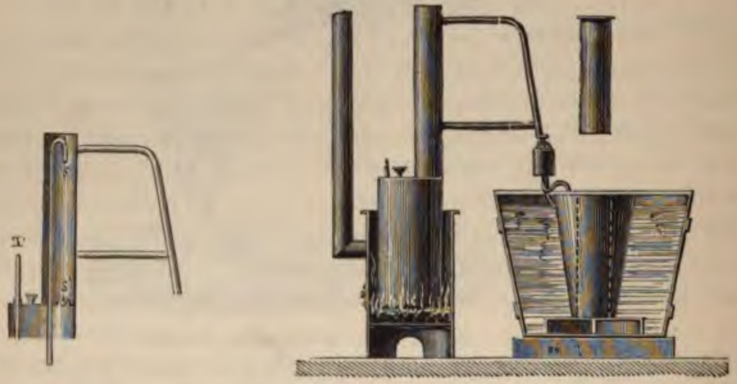


Fig. 243. Carré's Apparatus. Fig. 244.

In the first part of the experiment, which is represented in the figure, the boiler is placed upon a fire, and the temperature raised to 130°, while the cooler is surrounded with cold water. Ammoniacal gas is given off, passes into the cooler by the valve *s'* opening upwards, and is condensed in the numerous cells above mentioned. This first part of the operation, in the small machines for domestic use, occupies about three-quarters of an hour. In the second part of the operation, the cylindrical vessel containing the water to be frozen is placed in the central space; the cooler is surrounded with an envelope of felt, which is a very bad conductor of heat, and the boiler is immersed in cold water. The water in the boiler, as it cools, is able again to receive and dissolve the gas, which enters by the valve *s* of the bent siphon-shaped tube. The liquid ammonia in the cooler accordingly evaporates with great rapidity, producing a fall of temperature which freezes the water in the inclosed vessel.

253. Solidification of Carbonic Acid.—When a small orifice is opened in a vessel containing liquid carbonic acid, evaporation proceeds so rapidly that the cold resulting from it freezes a portion of the vapour, which takes the form of fine snow, and may be collected in considerable quantity.

This carbonic acid snow, which was first obtained by Thilorier, is readily dissolved by ether, and forms with it one of the most intense freezing mixtures known. By immersing tubes containing liquefied gases in this mixture, Faraday succeeded in reducing several of them, including carbonic acid, cyanogen, and nitrous oxide, to the form of clear transparent ice, the fall of temperature being aided, in some of his experiments, by employing an air-pump to promote more rapid evaporation of carbonic acid from the mixture. By the latter process he was enabled to obtain a temperature of $-166°$ F. ($-110°$ C.) as indicated by an alcohol thermometer, the alcohol itself being reduced to the consistence of oil. Despretz, by means of the cold produced by a mixture of solid carbonic acid, liquid nitrous oxide, and ether, rendered alcohol so viscid that it did not run out when the vessel which contained it was inverted.

CHAPTER XXVI.

EBULLITION.

254. Ebullition.—When a liquid contained in an open vessel is subjected to a continual increase of temperature, it is gradually changed into vapour, which is dissipated in the surrounding atmosphere. This action is at first confined to the surface; but after a certain time bubbles of vapour are formed in the interior of the liquid, which rise to the top, and set the entire mass in motion with more or less vehemence, accompanied by a characteristic noise; this is what is meant by *ebullition* or *boiling.*

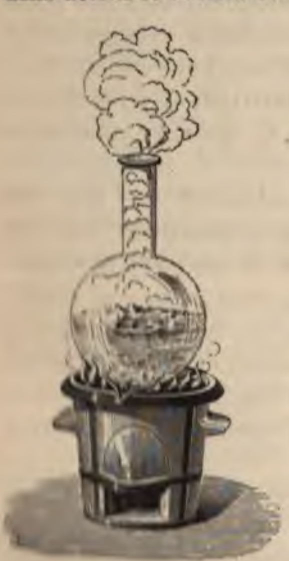


Fig. 245.—Ebullition.

If we observe the gradual progress of this phenomenon,—for example, in a glass vessel containing water, we shall perceive that, after a certain time, very minute bubbles are given off; these are bubbles of dissolved air. Soon after, at the bottom of the vessel, and at those parts of the sides which are most immediately exposed to the action of the fire, larger bubbles of vapour are formed, which decrease in volume as they ascend, and disappear before reaching the surface. This stage is accompanied by a peculiar sound, indicative of approaching ebullition, and the liquid is said to be *singing.* The sound is probably caused by the collapsing of the bubbles as they are condensed by the colder water through which they pass. Finally, the bubbles increase in number, growing larger as they ascend, until they burst at the surface, which is thus kept in a state of agitation; the liquid is then said to boil.

255. Laws of Ebullition.—1. *At the ordinary pressure, ebullition commences at a temperature which (roughly speaking) is definite for each liquid.*

This law is analogous to that of fusion (§ 225). It follows from this that the boiling-point of any liquid is a *specific* element, serving to determine its nature.

The following table gives the boiling-points of several liquids at the pressure of 760 millimetres:—

Sulphurous acid,	−10° C.	Spirits of turpentine,	+130° C.
Hydrochloric ether,	+11°	Phosphorus,	290°
Common ether,	37°	Concentrated sulphuric acid,	325°
Alcohol,	79°	Mercury,	353°
Distilled water,	100°	Sulphur,	440°

2. *The temperature, in ordinary circumstances, remains constant during ebullition.* If a thermometer be introduced into the glass vessel of Fig. 245, the temperature will be observed to rise gradually during the different stages preceding ebullition; but, when active ebullition has once commenced, no further variation of temperature will be observed. This phenomenon points to the same conclusion as the cold produced by evaporation.

Since, notwithstanding the continuous action of the fire, the temperature remains constant, the conclusion is inevitable, that all the heat produced is employed in doing the work necessary to change the liquid into vapour. The constancy of temperature during ebullition explains the fact that vessels of pewter, tin, or any other easily fusible metal, may be safely exposed to the action of even a very hot fire, provided that they contain water, since the liquid remains at a temperature of about 100°, and its contact prevents the vessel from over-heating.

3. *The elastic force of the vapour given off during ebullition is equal to the pressure of the external air.*

This important proposition may be experimentally demonstrated in the following manner:—

We take a bent tube A, open at the longer extremity, and closed at the shorter. The short branch is filled with mercury, all but a small space containing water; in the long branch the mercury stands a little higher than the bend. Water is now boiled in a glass vessel, and, during ebullition, the bent tube is plunged into the steam. The water occupying the upper part of the short branch is partially converted into steam, the mercury falls, and it *assumes the same* *level in both branches.* Thus the pressure exerted by the atmosphere at the open extremity of the tube is exactly equal to that exerted by the vapour formed by water in ebullition.

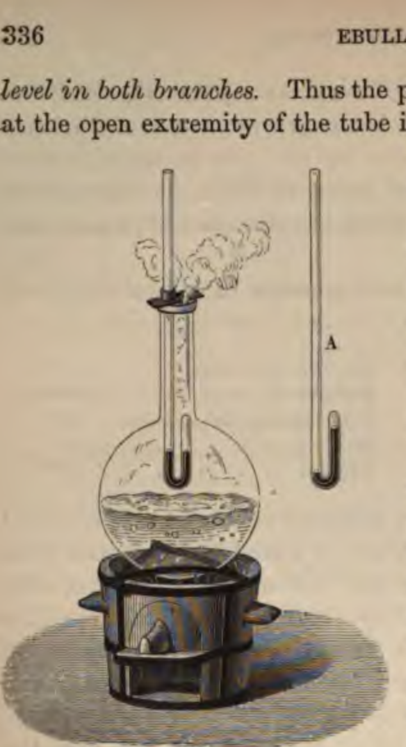
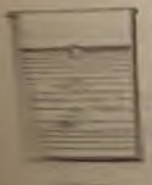


Fig. 246.—Tension of Vapour during Ebullition.

256. Theory of Ebullition.—This latter circumstance supplies the true physical definition of ebullition. *A liquid is in ebullition when it gives off vapour of the same tension as the atmosphere above it.*

The necessity of this equality of tension is easily explained. If a bubble of vapour exists in the interior of a liquid as at *m* (Fig. 247), it is subject to a pressure exceeding atmospheric by the weight of the liquid above it. As the bubble rises, the latter element of pressure becomes less, and the tension of the vapour composing the bubble accordingly diminishes, until it is reduced to atmospheric pressure on reaching the surface.

The boiling-point of a liquid is therefore necessarily fixed, since it is the temperature at which the tension of the vapour at saturation is equal to that of the atmosphere. It must be remarked, however, that this temperature varies in the different layers of the liquid, and that it increases with the depth below the surface. Accordingly, in determining the second fixed point of the thermometer, we have stated that the instrument should be plunged into the steam, and not into the water.



257. Effect of Pressure upon the Boiling-point.—It evidently follows from the foregoing considerations that the boiling-point of a liquid must vary with the pressure on the surface; and experiment shows that this is the case. Water, for instance, boils at 100° under the external pressure of 760 millimetres; but if the [illegible] ebullition occurs at a lower temperature. Under th[illegible] air-pump, water may be made to boil at any temperature between 0° and 100°. In Carré's apparatus (Fig. 239) the water in the glass bottle is observed to enter into active ebullition a few moments before the appearance of the ice. The reason, therefore, why boiling water has come to be associated in our minds with a fixed temperature is that the variations of atmospheric pressure are comparatively small.

At Paris, for instance, the external pressure varies between 720 and 790 millimetres (28·3 and 31·1 inches), and the boiling-point, in consequence, varies from 98·5° to 101·1°.

258. Franklin's Experiment.—The boiling of water at a temperature lower than 100° may be shown by the following experiment:—

A little water is boiled in a flask for a sufficient time to expel most of the air contained in it. The flask is then removed from the source of heat, and is at the same time securely corked. To render the exclusion of air still more certain, it may be inverted with the corked end immersed in water which has been boiled. Ebullition ceases almost immediately; but if cold water be now poured over the vessel, or, better still, if ice be applied to it, the liquid again begins to boil, and continues to do so for a considerable time. This fact may easily be explained: the contact of the cold water or the ice lowers the temperature and tension of the steam which presses upon the surface of the liquid, and the decrease of tension causes the renewal of ebullition.

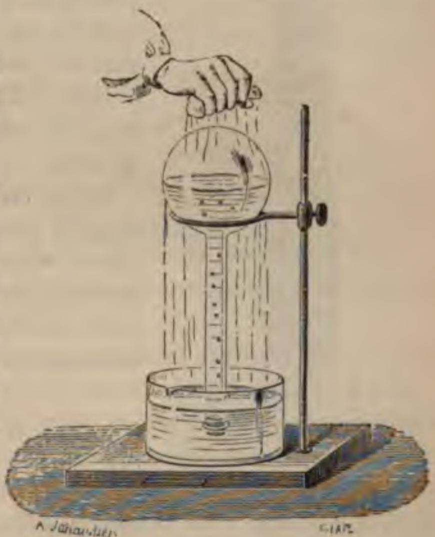


Fig. 243.—Franklin's Experiment.

260. Determination of Heights by Boiling-point.—Just as we can determine the boiling-point of water when the external pressure is given, so, if the boiling-point be known, we can determine the external pressure. In either case we have simply to refer to a table of maximum tensions of aqueous vapour at different temperatures.

As the barometer is essentially unsuitable for portability, Wollaston proposed to substitute the observation of boiling-points as a means of determining pressures. For this purpose he employed a thermometer with a large bulb and with a scale extending only a few degrees above and below 100°. He called this instrument the barometric thermometer.

Regnault has constructed a small instrument for the same purpose, which he calls the *hypsometer*. It consists of a little boiler heated by a spirit-lamp, and terminating in a telescope tube with an opening at the side through which the steam escapes. A thermometer dips into the steam, and projects through the top of the tube so as to allow the temperature of ebullition to be read.

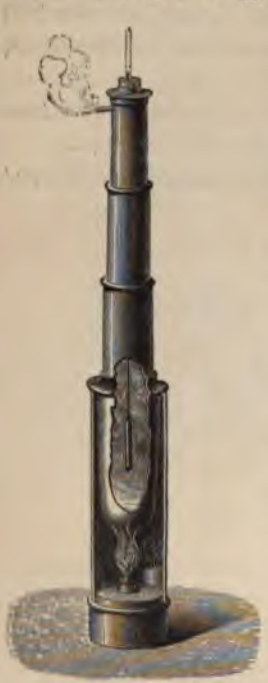


Fig. 250.—Hypsometer.

This temperature at once gives the atmospheric pressure by reference to a table of vapour-tensions, and the subsequent computations for determining the height are the same as when the barometer is employed (§ 112).

When only an approximate result is desired, it may be assumed that the height above sea-level is sensibly proportional to the difference between the observed boiling-point and 100° C., and Soret's formula[1] may be employed, viz.:

$$h = 295\ (100 - t),$$

where h is expressed in metres and t in degrees Centigrade.

Thus, at Quito, where the boiling-point of water is about 90·1°, the height above sea-level would be $9{\cdot}9 \times 295 = 2920$ metres, which agrees nearly with the true height 2808 metres.

At Madrid, at the mean pressure, the boiling-point is 97·8°, which gives $2{\cdot}2 \times 295 = 649$ metres; the actual height being 610 metres.

261. Papin's Digester.—While a decrease of pressure lowers the boiling-point, an increase of pressure raises it. Accordingly, by putting the boiler in communication with a reservoir containing air at the pressure of several atmospheres, we can raise the boiling-point to 110°, 115°, or 120°; a result often of great utility in the arts. But in

---

[1] If h be expressed in feet, and t in degrees Fahrenheit, the formula becomes

$$h = 538\ (212 - t).$$

order that the liquid may actually enter into ebullition, the space above the liquid must be sufficiently large and cool to allow of the condensation of the steam. In a confined vessel, water may be raised to a higher temperature than would be possible in the open air, but it will not boil. This is the case in the apparatus invented by the celebrated Papin, and called after him *Papin's digester*. It is a bronze vessel of great strength, covered with a lid secured by a powerful screw. It is employed for raising water to very high temperatures, and thus obtaining effects which would not be possible with water at 100°, such for example as dissolving the gelatine contained in bones.

It is to be observed that the tension of the steam increases rapidly with the temperature, and may finally acquire an enormous power. Thus, at 200°, the pressure is that of 16 atmospheres, that is about 240 pounds on the square inch. In order to obviate the risk of explosion, Papin introduced a device for preventing the pressure from exceeding a definite limit. This invention has since been applied to the boilers of steam-engines, and is well known as the *safety-valve*. It consists of an opening, closed by a conical valve or stopper, which is pressed down by a lever loaded with a weight. Suppose the area of the lower end of the stopper to be 1 square inch, and that the pressure is not to exceed 10 atmospheres, corresponding to a temperature of 180°. The magnitude and position of the weight are so arranged that the pressure on the hole is 10 times 15 pounds. If the tension of the steam exceed 10 atmospheres, the lever will be raised, the steam will escape, and the pressure will thus be relieved.

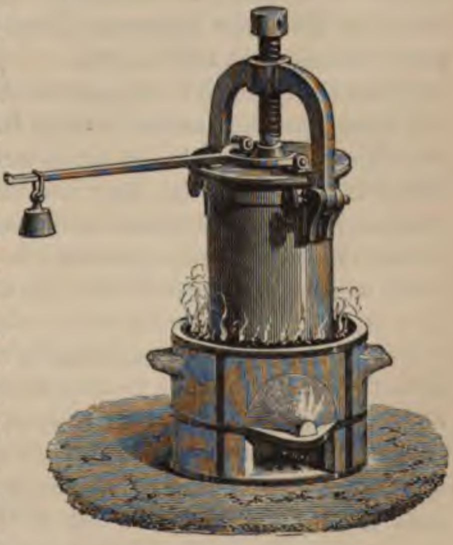


Fig. 251.—Papin's Digester.

When the tension of the steam contained in the digester has become considerable, if the lever be raised, so as to permit some steam to escape, it rushes out with a loud noise, and produces a cloud in the air. On placing the hand in this cloud, scarcely any sensation of heat is experienced, whereas, on performing the same experiment with steam at the ordinary pressure, the hand would certainly be scalded. This apparently paradoxical result is completely in accordance with the principles which have already been stated more than once. The steam formed at 100°, being at atmospheric pressure, preserves its pressure and temperature on issuing into the air. On the other hand, the steam generated in Papin's digester has a pressure greatly exceeding that of the atmosphere, and accordingly expands rapidly upon its exit, and thus performs work in forcing back the external air. The performance of this work is accompanied by the loss of an equivalent quantity of heat, and the temperature of the jet is consequently considerably lowered.

262. Boiling-point of Saline Solutions.—When water holds saline matters in solution, the boiling-point rises as the proportion of saline matter in the water increases. Thus with sea-salt the boiling-point can be raised from 100° to 108°.

When the solution is not saturated, the boiling-point is not fixed, but rises gradually as the mixture becomes concentrated; but at a certain stage the salt begins to be precipitated, and the temperature then remains invariable. This is to be considered the normal boiling-point of the saturated solution. Supersaturation, however, sometimes occurs, the temperature gradually rising above the normal boiling-point without any deposition of the salt, until all at once precipitation begins, and the thermometer falls several degrees.

The steam emitted by saline solutions consists of pure water, and it is frequently asserted to have the same temperature as the steam of pure water boiling under the same pressure; but the experiments of Magnus and others have shown that this is not the case. Magnus, for example,[1] found that when a solution of chloride of calcium was boiling at 107°, a thermometer in the steam indicated 105¼°, and when by concentration the boiling-point had risen to 116°, the thermometer in the steam indicated 111·2°.

These and other observations seem to indicate that the steam emitted by a saline solution when boiling, is in the condition in which the steam of pure boiling water would be, if heated, under atmospheric pressure, to the temperature of the boiling solution. It can therefore be cooled down to the boiling-point of pure water without undergoing any liquefaction. When cooled to this point, it becomes saturated, and precisely resembles the steam of pure water boiling under the same pressure. When saturated steam loses heat, it does not cool, but undergoes partial liquefaction, and it does not become completely liquefied till it has lost as much heat as would have cooled more than a thousand times its weight of superheated[1] steam one degree Centigrade.

---

[1] Poggendorff's *Annalen*, cxii. p. 415.

262 A. Boiling-point of Liquid Mixtures.—A mixture of two liquids which have an attraction for each other, and will dissolve each other freely in all proportions—for example, water and alcohol—has a boiling-point intermediate between those of its constituents. But a mechanical mixture of two liquids between which no solvent action takes place—for example, water and sulphide of carbon—has a boiling-point lower than either of its constituents. If steam of water is passed into liquid sulphide of carbon, or if sulphide of carbon vapour is passed into water, a mixture is obtained which boils at 42·6° C., being four degrees lower than the boiling-point of sulphide of carbon alone. This apparent anomaly is a direct consequence of the laws of vapours stated in § 244; for the boiling-point of such a mixture is the temperature at which the sum of the vapour-tensions of the two independent ingredients is equal to one atmosphere.

263. Influence of Dissolved Air upon the Boiling-point.—The presence of air in the midst of the liquid mass is a necessary condition of regularity of ebullition, and of its production at the normal temperature; this is shown by several convincing experiments.

1. *Donny's Experiment.*—We take a glass tube bent twice, and terminated at one of its extremities by a series of bulbs. The first step is to wash it carefully with alcohol and ether, finally leaving in it some diluted sulphuric acid. These operations are for the purpose of removing the solid particles adhering to the sides, which always detain portions of air. Water is then introduced and boiled long enough to expel the air dissolved in it, and while ebullition is proceeding, the end of the apparatus is hermetically sealed. The other extremity is now plunged in a strong solution of chloride of calcium, which has a very high boiling-point, and the tube is so placed that all the water shall lie in this extremity; it will then be found that the temperature may be raised to 135° without producing ebullition.

---

[1] That is steam heated above the temperature of saturation. Philosophically speaking, superheated steam is merely nonsaturated steam; but the name is never used except where the temperature exceeds the atmospheric boiling-point.

At about this temperature bubbles of steam are seen to be formed, and the entire liquid mass is thrown forward with great violence.

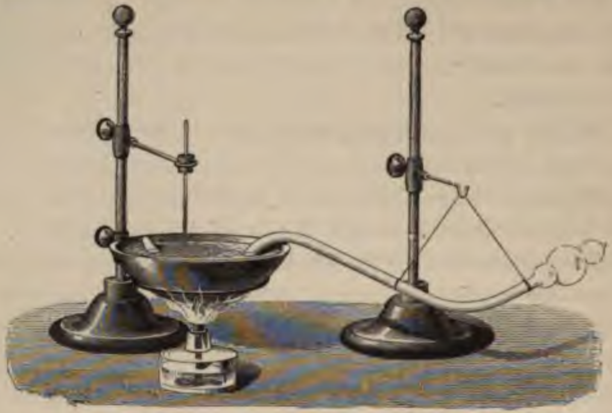


Fig. 252.—Donny's Experiment.

The bulbs at the end of the tube are intended to diminish the shock thus produced.

2. *Dufour's Experiment.*—This experiment is still more decisive. A mixture of linseed-oil and oil of cloves, whose respective densities are about ·93 and 1·01, is so prepared that, for temperatures near 100°, the density of the whole is nearly that of water. This mixture is placed in a cubical box of sheet-iron, with two holes opposite each other, which are filled with glass, so as to enable the observer to perceive what is passing within. The box is placed in a metallic envelope, which permits of its being heated laterally. When the temperature of 120° has been reached, a large drop of water is allowed to fall into the mixture, which, on reaching the bottom of the box, is partially converted into vapour, and breaks up into a number of smaller drops, some of which take up a position between the two windows, so as to be visible to the observer. The temperature may now be raised to 140°, 150°, or even 180°, without producing evaporation of any of these drops. Now the maximum tension of steam at 180° is equal to 10 atmospheres, and yet we have the remarkable phenomenon of a drop of water remaining liquid at this temperature under no other pressure than that of the external air increased by an inch or two of oil. The reason is that the air necessary to evaporation is not supplied. If the drops be touched with a rod of metal, or, better still, of wood, they are immediately converted into vapour

with great violence, accompanied by a peculiar noise. This is explained by the fact that the rods used always carry a certain quantity of condensed air upon their surface, and by means of this air the evaporation is produced. The truth of this explanation is proved by the fact, that when the rods have been used a certain number of times, they lose their power of provoking ebullition, owing, no doubt, to the exhaustion of the air which was adhering to their surfaces.

3. *Production of Ebullition by the formation of Bubbles of Gas in the midst of a Liquid.*—A retort is carefully washed with sulphuric acid, and then charged with water slightly acidulated, from which the air has been expelled by repeated boiling. The retort communicates with a manometer and with an air-pump. The air is exhausted until a pressure of only 150 millimetres is attained, corresponding to 60° as boiling-point. Dufour has shown that under these conditions the temperature may be gradually raised to 75° without producing ebullition. But if, while things are in this condition, a current of electricity is sent through the liquid by means of two platinum wires previously immersed in it, the bubbles of oxygen and hydrogen which are evolved at the wires immediately produce violent ebullition, and a portion of the liquid is projected explosively, as in Donny's experiment.

From these experiments we may conclude that liquid, when not in contact with gas, has a difficulty in *making a beginning* of vaporization, and may hence remain in the liquid state even at temperatures at which vaporization would upon the whole involve a fall of potential energy.

That vapour (as well as air) can furnish the means of overcoming this difficulty, is established by the fact noted by Professor G. C. Foster,[1] that when a liquid has been boiling for some time in a retort, it sometimes ceases to exhibit the movements characteristic of ebullition, although the amount of vapour evolved at the surface, as measured by the amount of liquid condensed in the receiver, continues undiminished. In these circumstances, it would appear that the superficial layer of liquid, which is in contact with its own vapour, is the only part that is free to vaporize.

The preceding remarks explain the reluctance of water to boil in glass vessels carefully washed, and the peculiar formation, in these circumstances, of large bubbles of steam, causing what is called *boil-*

---

[1] Watts's *Dictionary of Chemistry*, art. "Heat," p. 88.

ing by bumping. In the case of sulphuric acid, the phenomenon is much more marked; if this liquid be boiled in a glass vessel, enormous bubbles are formed at the sides, which, on account of the viscous nature of the liquid, raise the mass of the liquid above them, and then let it fall back with such violence as sometimes to break the vessel. This inconvenience may be avoided by using an annular brazier (Fig. 253), by means of which the upper part only of the liquid is heated.

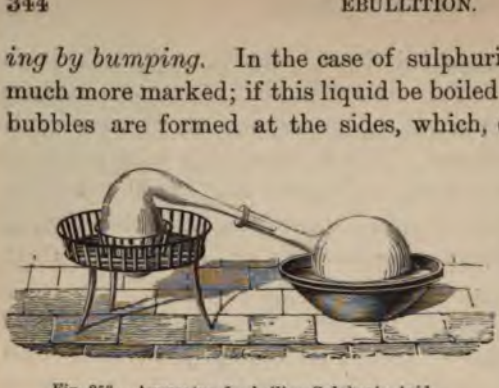


Fig. 253.—Apparatus for boiling Sulphuric Acid.

The ebullition of ether and alcohol presents some similar features, probably because these liquids dissolve the fatty particles on the surface of the glass, and thus adhere to the sides very strongly.

264. Spheroidal State.—This is the name given to a peculiar condition which is assumed by liquids when exposed to the action of very hot metals.

If we take a smooth plate of iron or silver, and let fall a drop of water upon it, the drop will evaporate more rapidly as the temperature of the plate is increased up to a certain point. When the temperature of the plate exceeds this limit, which, for water, appears to be about 150°, the drop assumes a spheroidal form, rolls about like a ball or spins on its axis, and frequently exhibits a beautiful rippling, as represented in the figure. While in this condition, it evaporates much more slowly than when the plate was at a lower temperature. This latter circumstance is important, and is easily verified by experiment. If the plate be allowed to cool, a moment arrives when the globule of water flattens out, and boils rapidly away with a hissing noise.

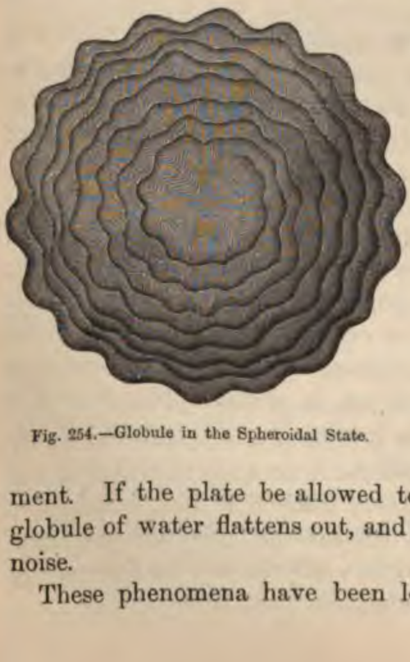


Fig. 254.—Globule in the Spheroidal State.

These phenomena have been long known, and were studied by

Leidenfrost and Klaproth; but the subject has recently been more completely investigated by Boutigny. All liquids are probably capable of assuming the spheroidal state. Among those which have been tested are alcohol, ether, liquid sulphurous acid, and liquid nitrous oxide. When in this state they do not boil. Sometimes bubbles of steam are seen to rise and burst at the top of the globule, but these are always owing to some roughness of the surface, which prevents the steam from escaping in any other way; when the surface is smooth, no bubbles are observed.

If the temperature of the liquid be measured by means of a thermometer with a very small bulb, or a thermo-electric junction, it is always found to be below the boiling-point.

265. Freezing of Water and Mercury by means of the Spheroidal State.—This latter property enables us to obtain some very striking and paradoxical results. The boiling-point of liquid sulphurous acid is −10° C., and that of liquid nitrous oxide is about −70° C. If a silver or platinum crucible be heated to redness by a powerful lamp, and some liquid sulphurous acid be then poured into it, this latter assumes the spheroidal state; and drops of water let fall upon it are immediately frozen. Mercury can in like manner be frozen in a red-hot crucible by employing liquid nitrous oxide in the spheroidal state.

These experiments are due to Boutigny, who called attention to them as remarkable exceptions to the usual tendency of bodies to equilibrium of temperature. The exception is of the same kind as that presented by a vessel of water boiling at a constant temperature of 100° over a hot fire, the heat received by the liquid being in both cases expended in producing evaporation.

266. The Metal not in Contact with the Liquid.—The basis of the entire theory of liquids in the spheroidal state is the fact that the liquid and the metal plate do not come into contact. This fact can be proved by direct observation.

The plate used must be quite smooth and accurately levelled. When the plate is heated, a little water is poured upon it, and assumes the spheroidal state. By means of a fine platinum wire which passes into the globule, the liquid is kept at the centre of the metal plate. It is then very easy, by placing a light behind the globule, to see distinctly the space between the liquid and the plate. The appearance thus presented may be easily thrown on a screen by means of the electric light.

The interruption of contact can also be proved by connecting (through a galvanometer) one pole of a battery with the hot plate, while a wire from the other pole is dipped in the liquid. The current refuses to circulate if the liquid is in the spheroidal state, but is immediately established when, on cooling the plate, the liquid begins to boil.

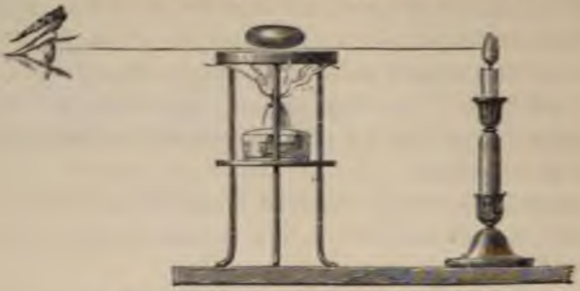


Fig. 255.—Separation between Globule and Plate.

This separation is maintained by the rush of steam from the under-surface of the globule, which is also the cause of the peculiar movements above described.

In consequence of the separation, heat can only pass to the globule by radiation, and hence its comparatively low temperature is accounted for.

The absence of contact between a liquid and a metal at a high temperature may be shown by several experiments. If, for instance, a ball of platinum be heated to bright redness, and plunged (Fig. 256) into water, the liquid is seen to recede on all sides, leaving an envelope of vapour round the ball. This latter remains red for several seconds, and contact does not take place till its temperature has fallen to about 150°. An active ebullition then takes place, and an abundance of steam is evolved.

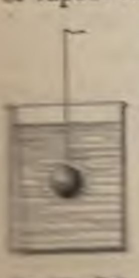


Fig. 256.—Red-hot Ball in Water.

If drops of melted sugar be let fall on water, they will float for a short time, though their density is greater than that of water (§ 79), contact being prevented by their high temperature. A similar phenomenon is observed when a fragment of potassium is thrown on water. The water is decomposed; its hydrogen takes fire and burns with a red flame; its oxygen combines with the potassium to form potash; and the globule of potash floats upon the surface without touching it, owing to the high temperature under which it is formed. After a few seconds the globule cools sufficiently to come into contact with the water, and bursts with a slight noise.

267. Distillation.—Distillation consists in boiling a liquid and condensing the vapour evolved. It enables us to separate a liquid from the solid matter dissolved in it, and to effect a partial separation of the more volatile constituent of a mixture from the less volatile.

The apparatus employed for this purpose is called a still. One of the simpler forms, suitable for distilling water, is shown in Fig. 257.

It consists of a retort *a*, the neck of which *c* communicates with a spiral tube *d d* called the *worm*, placed in the vessel *e*, which contains cold water. The water in the retort is raised to ebullition, the steam given off is condensed in the worm, and the *distilled water* is collected in the vessel *g*.

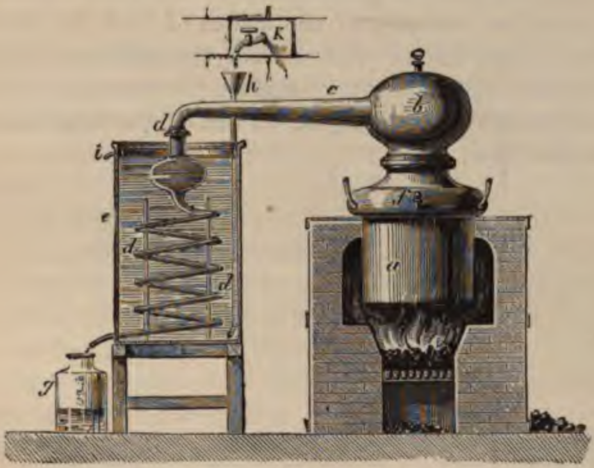


Fig. 257.—Still.

As the condensation of the steam proceeds, the water of the cooler becomes heated, and must be renewed; for this purpose a tube descending to the bottom of the cooler is supplied with a continuous stream of cold water from above, while the superfluous water flows out by the tube *i* at the upper part of the cooler. In this way the warm water, which rises to the top, is continually removed. The boiler is filled about three-quarters full, and the water in it can from time to time be renewed by the opening *f*; but it is advisable not to carry the process of distillation too far, and to throw away the liquid remaining in the boiler when its volume has been reduced to a fourth or a fifth of what it was originally. By exceeding this limit we run the risk of impairing the purity of the water by the carrying over of some of the solid matter contained in the liquid in the boiler.

269. Circumstances which Influence Rapidity of Evaporation.—In the case of a liquid exposed to the air, and at atmospheric temperature, the rapidity of evaporation increases with the extent of free surface, the dryness of the air, and the rapidity of renewal of the air immediately above the surface.

In the case of a liquid evaporated by boiling, the quantity evaporated in a given time is proportional to the heat received. This depends upon the intensity of the source of heat, the facility with which heat passes through the sides of the vessel, and the area of *heating surface,* that is to say, of surface (or more properly lamina) which is in contact with the liquid on one side, and with the source of heat on the other.

CHAPTER XXVII.

MEASUREMENT OF THE MAXIMUM TENSIONS OF VAPOURS.

270. Tension of Aqueous Vapour.—The knowledge of the maximum tension of the vapour of water at various temperatures is important, not only from a theoretical, but also from a practical point of view, inasmuch as this tension is the motive force in the steam-engine. Experiments for the purpose of determining the values of this element have accordingly been undertaken by several experimenters in different countries. The researches conducted by Regnault are especially remarkable for the range of temperature which they embrace, as well as for the number of observations which they include, and the extreme precision of the methods employed. Next to these in importance are the experiments of Magnus in Germany and of Fairbairn and Tate in England.

271. Dalton's Apparatus.—The first investigations in this subject which have any pretensions to accuracy were those of Dalton. The apparatus which he employed is represented in Fig. 259. Two barometric tubes A and B are inverted in the same cistern H; one is an ordinary barometer, the other a vapour-barometer; that is, a barometer in which a few drops of water have been passed up through the mercury. The two tubes, attached to the support CD, are surrounded by a cylindrical glass vessel containing water which can be raised to different temperatures by means of a fire. The first step is to fill the vessel with ice, and then read the difference of level of the mercury in the two tubes. This can be done by separating the fragments of ice. The difference thus observed is the tension of aqueous vapour at zero Centigrade. The ice is then replaced by water, and the action of the fire is so regulated as to give different temperatures, ranging between 0° and 100° C., each of which is preserved constant for a few minutes, the water being at the same time well stirred by means of the agitator *pq*, so as to insure uniformity of temperature throughout the whole mass. The difference of level in the two barometers is read off in each case; and we have thus the means of constructing, with the aid of graphical or numerical interpolation, a complete table of vapour-tensions from 0° to 100° C. At or about this latter temperature the mercury in the vapour-barometer falls to the level of the cistern; and the method is therefore inapplicable for higher temperatures. Such a table was constructed by Dalton.

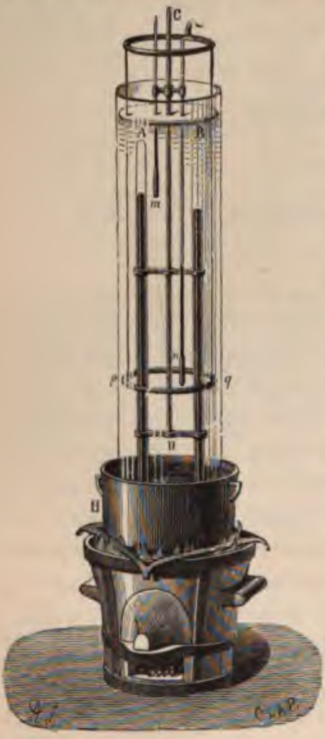


Fig. 259.—Dalton's Apparatus.

272. Regnault's Modifications.—Dalton's method has several defects. In the first place, it is impossible to insure that the temperature shall be everywhere the same in a column as long as that which is formed by the vapour at 70°, 75°, and higher temperatures. In the second place, there is always a good deal of uncertainty in observing the difference of level through the sides of the cylindrical glass vessel. Regnault employed this method only up to the temperature of 50° C. At this temperature the tension of the vapour is only about 9 centimetres (less than 4 inches) of mercury, and it is thus unnecessary to heat the barometers throughout their entire length. The improved apparatus is represented in Fig. 260. The two barometric tubes, of an interior diameter of 14 millimetres, traverse two holes in the bottom of a metal box. In one of the sides of the box is a large opening closed with plate-glass, through which the necessary observations can be made with great accuracy. On account of the shortness of the liquid column it was very easy, by bringing a spirit-lamp within different distances of the box, to maintain for a sufficient time any temperature between 0° and 50° C.

The difference of level between the two mercurial columns should be reduced to 0° C. by the ordinary correction. We should also take into consideration the short column of water which is above the mercury in the vapour barometer, and which, by its weight, produces a depression that may evidently be expressed in mercury by dividing the height of the column by 13·59.

To adapt this apparatus to low temperatures, it is modified in the following way. The upper extremity of the vapour barometer tube is drawn out and connected with a small copper tube of three branches, one of which communicates with an air-pump, and another with a glass globe of the capacity of about 500 cubic centimetres. In the interior of this globe is a small bulb of thin glass containing water, from which all the air has been expelled by boiling. The globe is several times exhausted of air, and after each exhaustion is refilled with air which has been passed over desiccating substances. After the last exhaustion, the tube which establishes communication with the air-pump is hermetically sealed, the box is filled with ice, and the tension at zero of the dry air left behind in the globe by the air-pump is measured; it is of course exceedingly small. Heat is then applied to the globe, the little bulb bursts, and the globe, together with the space above the mercury, is filled with vapour. This form of apparatus can also be employed to measure tensions at temperatures up to 50°, the only difference being that the ice is replaced by water at different temperatures, allowance being made, in each case, for the elastic force of the unexhausted air.

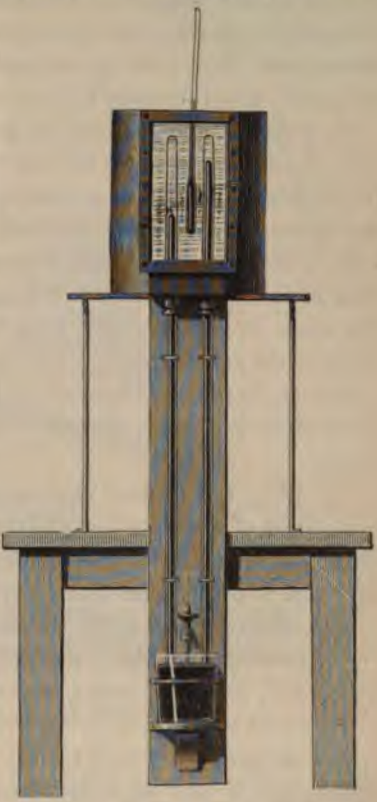


Fig. 260.—Modified Form of Dalton's Apparatus.

In the case of temperatures below zero, the box is no longer required, and the globe alone is placed in a vessel containing a freezing mixture. The barometric tubes are surrounded by the air of the apartment.

In this case the space occupied by the vapour is at two different temperatures in different parts, but it is evident that equilibrium can exist only when the tension is the same throughout. But the tension of the vapour in the globe can never exceed the maximum tension for the actual temperature; this must therefore be the tension throughout the entire space, and is consequently that which corresponds to the difference of level observed.

In reality what happens is as follows:—The low temperature of the globe causes some of the vapour to condense; equilibrium is consequently destroyed, a fresh quantity of vapour is produced, enters the globe, and is there condensed, and so on, until the tension is everywhere the same as the maximum tension due to the temperature of the globe. This condensation of vapour in the cold part of the space was utilized by Watt in the steam-engine; it is the *principle of the condenser.*

Before Regnault, Gay-Lussac had already turned this principle to account in a similar manner for the measurement of low temperatures.

By using chloride of calcium mixed with successively increasing quantities of snow or ice, the temperature can be brought as low as −32°C. (−25·6° F.), and it can be shown that the tension of the vapour of water is quite appreciable even at this point.

273. Measurement of Maximum Tensions for Temperatures above 50°.—In investigating the tension of the vapour of water at temperatures above 50°, Regnault made use of the fact that the maximum tension of steam at the boiling-point is equal to the external pressure.

His apparatus consists (Fig. 261) of a copper boiler containing water which can be raised to different temperatures indicated by very delicate thermometers. The vapour produced passes through a tube inclined upwards, which is kept cool by a constant current of water; in this way the experiment can be continued for any length of time, as the vapour formed by ebullition is condensed in the tube, and flows back into the boiler. The tube leads to the lower part of a large reservoir, in which the air can be either rarefied or compressed at will. This reservoir is in communication with a manometer. The apparatus shown in the figure is that employed for pressures not exceeding 5 atmospheres. Much greater pressures, extending to 28 atmospheres, can be attained by simply altering the dimensions of the apparatus without any change in its principle. The manometer employed in this case was the same as that used in testing Boyle's law, consisting of a long column of mercury (§ 121).

In using this apparatus, the air in the reservoir is first rarefied until the water boils at about 50° C.; the occurrence of ebullition being recognized by its characteristic sound, and by the temperature remaining invariable. This steadiness of temperature is of great advantage in making the observations, inasmuch as it enables the thermometers to come into perfect equilibrium of temperature with the water. The tension indicated by the manometer during ebullition is exactly that of the vapour produced. By admitting air into the reservoir, the boiling-point is raised by successive steps until it reaches 100°. After this, air must be forced into the reservoir by a compression-pump.

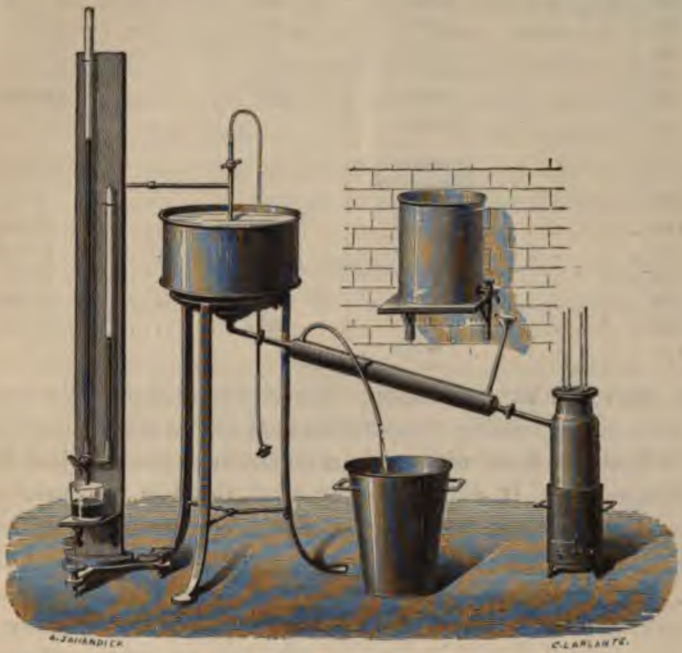


Fig. 261.—Regnault's Apparatus for High Temperatures.

The following is an abstract of the results thus obtained:—

Temperatures Centigrade.	Tensions in Millimetres of Mercury.	Temperatures Centigrade.	Tensions in Millimetres of Mercury.
−32°	0·32	5°	6·53
−20	0·93	10	9·17
−10	2·09	15	12·70
− 5	3·11	20	17·39
0	4·60	25	23·55

Temperatures Centigrade.	Tensions in Millimetres of Mercury.	Temperatures Centigrade.	Tensions in Millimetres of Mercury.
30°	31·55	70°	233·09
35	41·82	75	288·51
40	54·91	80	354·64
45	71·39	85	433·04
50	91·98	90	525·45
55	117·47	95	633·77
60	148·70	100	760·00
65	186·94		

	Tensions in Atmospheres.		Tensions in Atmospheres.
100°	1	180°	9·929
121	2·025	189	12·125
134	3·008	199	15·062
144	4·000	213	19·997
152	4·971	225	25·125
159	5·966	239	27·534
171	8·036		

274. Curves of Vapour-tension.—The comparison of these tensions with their corresponding temperatures affords no clue to any simple relation between them which might be taken as the physical law of the phenomena. It would appear that the law of variation of maximum tensions is incapable of being thrown into any simple expression—judging at least from the failure of all efforts hitherto made. An attentive examination of the above table will enable us to assert only that the maximum tension varies very rapidly with the temperature. Thus between 0° and 100° the variation is only 1 atmosphere, but between 100° and 200° it is about 15, and between 200° and 230° about 13 atmospheres.

The clearest way of representing to the mind the law according to which vapour-tension varies with temperature, is by means of a curve whose ordinates represent vapour-tensions, while the abscissæ represent the corresponding temperatures. Such a curve is exhibited in Fig. 262. Lengths proportional to the temperatures, reckoned from 0° C., are laid off on the base-line (called the line of abscissæ), and perpendiculars (called ordi-

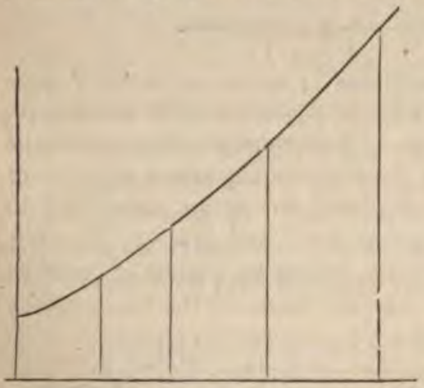


Fig. 262.

nates) are erected at their extremities, the lengths of these perpendiculars being made proportional to the vapour-tensions. The scales employed for the two sets of lengths are of course quite independent of one another, their selection being merely a question of convenience. The curve itself is obtained by joining the extremities of the perpendiculars, taking care to avoid sudden changes of direction; and it not only serves to convey to the mind an idea of the amounts of vapour-tensions and their rates of variation at different temperatures, but also furnishes the readiest means of determining the vapour-tensions at temperatures intermediate between those of observation (see §88 B).

It will be noticed that the curve becomes steeper as the temperature increases, indicating that the tension increases faster than the temperature.

275. Empirical Formulæ.—Though all attempts at finding a rational formula for vapour-tension in terms of temperature have hitherto failed, it is easy to devise empirical formulæ which yield tolerably accurate results within a limited range of temperature; and by altering the values of the constants in such a formula by successive steps, it may be adapted to represent in succession the different portions of the curve above described.

The simplest of these approximate formulæ[1] is that of Dulong and Arago, which may be written—

$$\left(\frac{40 + \mathrm{C}}{140}\right)^5 \quad \text{or} \quad \left(\frac{38 + \mathrm{F}}{250}\right)^5,$$

and gives the maximum tension *in atmospheres*, corresponding to the temperature C° Centigrade, or F° Fahrenheit. This formula is rigorously correct at 100° C., and gives increasing errors as the temperature departs further from this centre, the errors amounting to about 1½ per cent. at the temperatures 80° C. and 225° C. Hence it appears that between these limits the maximum tension of aqueous vapour is nearly proportional to the fifth power of the excess of the temperature above —40° C.

276. Tensions of the Vapours of Different Liquids.—Dalton held that *the vapours of different liquids have equal tensions at temperatures equally removed from their boiling-points.* Thus the boiling-point of alcohol being 78°, the tension of alcohol vapour at 70° should be equal to that of the vapour of water at 92°. If this law were correct, it would only be necessary to know the boiling-point of any liquid in order to estimate the tension of its vapour at any given temperature; but subsequent experiment has shown that the law is far from being rigorously exact, though it is approximately correct for temperatures differing by only a few degrees from the boiling-points.

---

[1] For a more accurate formula, see *Rankine on Steam-engine*, p. 237.

Regnault has performed numerous experiments on the vapour-tensions of some of the more volatile liquids, employing for this purpose the same form of apparatus which had served for determining the tensions of aqueous vapour. The following are some of his results:—

Vapour of Alcohol.

Temperatures Centigrade.	Tensions in Millimetres.	Temperatures Centigrade.	Tensions in Millimetres.
−20°	3·24	+ 30°	78·52
0	12·70	100	1697·55
+10	24·23	155	6259·19

Vapour of Ether.

−20°	68·90	+ 30°	634·80
0	184·39	100	4953·30
+10	286·83	120	7719·20

Vapour of Sulphide of Carbon.

−20°	47·30	+ 30°	434·62
0	127·91	100	3325·15
+10	198·46	150	9095·94

277. Expression of Vapour-tension in Absolute Measure.—The maximum tension of a given vapour at a given temperature is, from its very nature, independent of geographical position, and should therefore, properly speaking, be denoted by one and the same number at all places. This numerical uniformity will not exist if the tension be expressed, as in the preceding sections, in terms of the length of a column of mercury which balances it. For example, in order to adapt Regnault's determinations to London, we must multiply them by the fraction $\frac{3456}{3457}$, inasmuch as 3456 millimetres of mercury exert the same pressure at London as 3457 at Paris. In general, to adapt determinations of pressure made at a place A, to another place B, we must multiply them by the fraction

$$\frac{\text{gravity at A}}{\text{gravity at B}}.$$

If the length of mercurial column at 0° C. which balances a vapour-tension at a given place be multiplied by the value of g (denoting intensity of gravity) at that place, the product may be called the *absolute value* of the vapour-tension; for the products thus obtained will be the same at all localities. This is the proper mode of treating determinations of vapour-tension made at various localities when it is desired to establish a rigorous comparison between them.

278. Laws of Combination by Volume.—It was discovered by Gay-Lussac, that when two or more gaseous elements at the same temperature and pressure enter into chemical combination with each other, the two following laws apply:—

1. The volumes of the components bear a very simple ratio to each other, such as 2 to 3, 1 to 2, or 1 to 1.

2. The volume of the compound has a simple ratio to the sum of the volumes of the components.

Ammonia, for example, is formed by nitrogen and hydrogen uniting in the proportion of one volume of the former to three of the latter, and the volume of the ammonia, if reduced to the same pressure as each of its constituents, is just half the sum of their volumes. Further investigation has led to the conclusion (which is now generally received, though hampered by some apparent exceptions), that these laws apply to all cases of chemical combination, the volumes compared being those which would be occupied respectively by the combining elements and the compound which they form, *when reduced to the state of vapour*, at such a temperature and pressure as to be very far removed from liquefaction, and consequently to possess the properties of what we are accustomed to call permanent gases.

It is obvious that if all gases and vapours were equally expansible by heat, the volume-ratios referred to in this law would be the same at all temperatures; and that, in like manner, if they were all equally compressible (whether obeying Boyle's law, or departing equally from it at equal pressures), the volume-ratios would be independent of the pressure at which the comparison was made.

In reality great differences exist between different vapours in both respects, and these inequalities are greater as the vapours are nearer to saturation. It is accordingly found that the above laws of volume-ratio often fail to apply to vapours when under atmospheric pressure and within a few degrees of their boiling-points, and that, in such cases, a much nearer fulfilment of the law is obtained by employing very high temperatures, or operating in inclosures at very low pressures.

278A. Relation of Vapour-densities to Chemical Equivalents.—Chemists have determined with great accuracy the combining proportions by weight of most of the elements. Hence the preceding laws can be readily tested for bodies which usually exist in the solid or liquid form, if we are able to compare the densities of their vapours. In fact, if two such elements combine in the ratio, by weight, of w_1 to w_2, we have

$$v_1 = \frac{w_1}{d_1}, \quad v_2 = \frac{w_2}{d_2},$$

v_1 v_2 d_1 d_2 denoting the volumes and densities of the vapours of weights w_1 w_2 of the two substances.

Hence we have the equation—

$$\frac{v_1}{v_2} = \frac{w_1}{w_2} \cdot \frac{d_2}{d_1},$$

which gives the required volume-ratio of the vapours, if the ratio of their densities be known.

The densities themselves will differ enormously according to the pressure and temperature at which they are taken, but their ratio will only vary by comparatively small amounts, and would not differ at all if they were equally expansible by heat, and equally compressible. Hence comparison will be facilitated by tabulating the ratios of the densities to that of some standard gas, namely air, under the same conditions of pressure and temperature, rather than the absolute densities. This is accordingly the course which is generally pursued, so generally indeed, that by the *vapour-density of a substance* is commonly understood the relative density as measured by this ratio.

The process most frequently employed for the determination of this element is that invented by Dumas.

279. Dumas' Method.—The apparatus consists of a glass globe B, containing the substance which is to be converted into vapour.

The globe is placed in a vessel C, containing some liquid which can be raised to a suitable temperature. If the substance to be operated on is one which can be vaporized at 100°C., the bath consists simply of boiling water. When higher temperatures are required, a saline solution, oil, or a fusible alloy is employed. In all cases, the liquid should be agitated, that its temperature may be the same in all parts. This temperature is indicated by the thermometer *t*.

When the substance in the globe has attained its boiling-point, evaporation proceeds rapidly, and the vapour escapes, carrying out the air along with it. When the vapour ceases to issue, we may assume, if the quantity of matter originally taken has been sufficiently large, that all the air has been expelled, and that the globe is full of vapour at the temperature given by the thermometer, and at the external pressure H. The globe is then hermetically sealed at the extremity *p* of the neck, which has been previously drawn out into a fine tube.

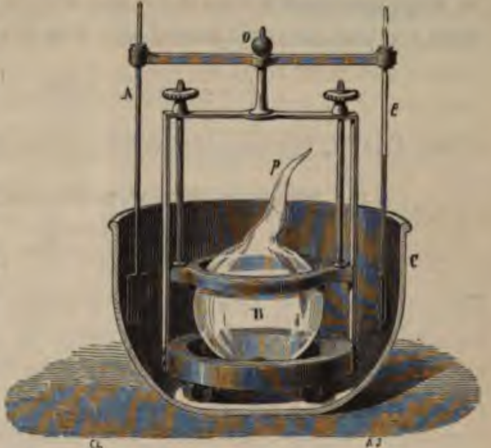


Fig. 263.—Dumas' Apparatus.

280. Calculation of the Experiment.—As already remarked, the densities of vapours given in treatises on chemistry express *the ratio of the weight of a given volume of the vapour to that of the same volume of air at the same temperature and pressure.* In order to deduce this ratio from the preceding experiment, we must first find the weight of the vapour. This is done by weighing the globe with its contents, after allowing it to cool. Suppose the weight thus found to be W. Before the experiment the globe had been weighed full of dry air at a known temperature t and pressure h. Suppose this weight to be W′; the difference W − W′ evidently represents the excess of the weight of the vapour above that of the air. If, then, we add W − W′ to the weight of the air, we shall evidently have the weight of the vapour. Now the weight of the air is easily deduced from the known volume of the globe. If V denote this volume at zero expressed in litres, the weight in grammes of the air contained in the globe at the time of weighing is

$$V(1+Kt)\ 1{\cdot}293 \times \frac{1}{1+at} \cdot \frac{h}{760},$$

K denoting the coefficient of cubical expansion of glass, and a the coefficient of expansion of air. The weight of the vapour contained in the globe is consequently

$$A = W - W' + V(1+Kt) \times 1{\cdot}293 \times \frac{1}{1+at} \cdot \frac{h}{760}.$$

Let H be the pressure, and T the temperature at the time of sealing the globe. The volume occupied by the vapour under these circumstances was V (1+KT). The density of the vapour will therefore be obtained by dividing A by the weight of this volume of air at the same temperature and pressure. But this weight is

$$A'=V\,(1+KT)\,.\,1{\cdot}293\,.\,\frac{1}{1+\alpha T}\,.\,\frac{H}{760};$$

hence, finally, the required relative density is

$$D=\frac{A}{A'}.=\frac{W-W'+V\,(1+Kt)\,.\,1{\cdot}293\,.\,\frac{1}{1+\alpha t}\,.\,\frac{h}{760}}{V\,(1+KT)\,.\,1{\cdot}293\,.\,\frac{1}{1+\alpha T}\,.\,\frac{H}{760}}.$$

The correctness of this formula depends upon the assumption that no air is left in the globe. In order to make sure that this condition is fulfilled, the point *p* of the neck of the globe is broken off under mercury; the liquid then rushes in, and, together with the condensed vapour, fills the globe completely, if no air has been left behind.

This last operation also affords a means of calculating the volume V; for we have only to weigh the mercury contained in the globe, or to measure it in a graduated tube, in order to ascertain its volume at the actual temperature, whence the volume at zero can easily be deduced.

281. Example.—In order better to illustrate the method, we shall take the following numerical results obtained in an investigation of the vapour-density of sulphide of carbon:—

Excess of weight of vapour above weight of air, W—W′=·3 gramme; temperature of the vapour T=59°; external pressure H=752·5 millimetres; volume of the globe at a temperature of 12°, 190 cubic centimetres; temperature of the dry air which filled the globe at the time of weighing, t=15°; pressure h=765; K= $\frac{1}{38700}$.

The volume V of the globe at zero is

$$\frac{190}{1+\frac{12}{38700}}=189{\cdot}94 \text{ cubic centimetres} = {\cdot}18994 \text{ litre.}$$

The weight of the air contained in the globe is

$${\cdot}18994\times1{\cdot}293\,.\left(1+\frac{12}{38700}\right)\cdot\frac{1}{1+12\times\,.\,00366}\cdot\frac{765}{760}={\cdot}23658 \text{ gramme.}$$

Weight of the vapour,

$${\cdot}23658+W-W'={\cdot}53658 \text{ gramme.}$$

The weight of the same volume of air at the same temperature and pressure is

$$\cdot 18994 \times 1\cdot 293 \left(1 + \frac{59}{38700}\right) \cdot \frac{1}{1 + \cdot 00366 \times 59} \cdot \frac{752\cdot 5}{760} = \cdot 20019 \text{ gramme.}$$

The density is therefore

$$\frac{\cdot 53658}{\cdot 20019} = 2\cdot 67.$$

Deville and Troost have effected several improvements in the application of Dumas' method to vapours at high temperatures. These temperatures are obtained by boiling various substances, such as chloride of zinc, cadmium, which boils at 860° C., or zinc, which boils at 1040° C. For temperatures above 800°, the glass globe is replaced by a globe of porcelain, which is hermetically sealed with the oxyhydrogen blowpipe. The globe itself serves as a pyrometer to determine the temperature; and since the weight of air becomes very inconsiderable at high temperatures, some heavier vapour, such as that of iodine, is substituted in its place. If we suppose, as we may fairly do, that at these high temperatures the coefficient of expansion of the vapour of iodine is the same as that of air, the temperature may easily be deduced from the weight of iodine contained in the globe. We subjoin a table of some relative densities of vapours obtained by this method:—

Water,	0·622	Phosphorus,	4·5
Alcohol,	1·6138	Cadmium,	3·94
Ether,	2·586	Chloride of aluminium,	9·347
Spirit of turpentine,	5·0130	Bromide of aluminium,	18·62
Iodine,	8·716	Chloride of zirconium,	8·1
Sulphur,	2·23	Sesquichloride of iron,	11·39

282. Limiting Values of Relative Densities.—In investigating the relative density of acetic acid vapour, Cahours found that it went on decreasing as the temperature increased, up to a certain point, after which no further change was observable. A similar circumstance is observed in the case of all substances, only in different degrees. The vapour of sulphur, for instance, has a relative density of 6·65 at 500° C., while at about 1000° C. it is only 2·23. This indicates that the vapours in question are more expansible by heat than air until the limiting temperatures are attained. Indeed it may be laid down as a general principle, that the nearer a vapour is to saturation the greater is the change produced in its absolute density by a given change whether of temperature or pressure. The limiting density-ratio is always that which it is most important to determine, and we should consequently take care that the temperature of the vapour is sufficiently high to enable us to obtain it.

283. Gay-Lussac's Method.—Gay-Lussac determined the density of the vapour of water and of some other liquids by a method a little more complicated than that described above, and which for that reason has not been generally adopted in the laboratory. We proceed to describe it, however, on account both of its historical interest and of the importance of the question which it has assisted in solving.

A graduated tube divided into cubic centimetres, suppose, is filled with mercury, and inverted in a cast-iron vessel containing the same liquid. The inverted tube is surrounded by a glass envelope containing water, as in Dalton's apparatus. A small glass bulb containing a given weight *w* (expressed in grammes) of distilled water is passed into the tube, and rises to the surface of the mercury. The temperature of the apparatus is then raised by means of a fire below, the bulb bursts, and the water which it contained is converted into vapour. If the quantity of water be not too great, it is all converted into vapour; this is known to be the case when, at the temperature of about 100°, the mercury stands higher in the tube than in the vessel, for if there were any liquid-water present, the space would be saturated, and the tension of the vapour would be equal to the external pressure. This arrangement accordingly gives the weight of a known volume of the vapour of water. This volume, which may at once be read upon the graduated tube, is equal to V (1+KT), V being the number of divisions occupied by the vapour. The temperature T is marked by a thermometer immersed in the water contained in the envelope. The tension of the vapour is evidently equal to the external pressure *minus* the height of the mercury in the tube.

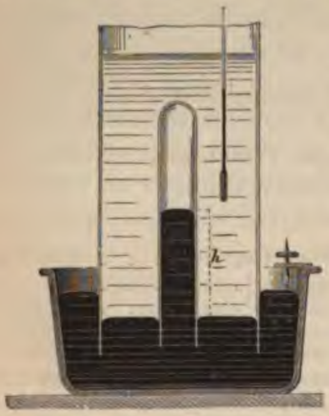


Fig. 264.—Gay-Lussac's Apparatus.

In order to find the relative density, we must divide *w* by the weight of a volume V (1+KT) of air at the temperature T and pressure H$-h$, giving

$$\frac{w}{V\ (1+KT) \times \cdot 001293 \times \frac{1}{1+aT} \cdot \frac{H-h}{760}}.$$

The relative density of the vapour of water, as thus determined by Gay-Lussac, is about $\frac{5}{8}$, or ·625. Several recent investigations have given as mean result ·622, which agrees with the theoretical density deduced from the composition of water.[1]

284. Volume of Vapour formed by a given Weight of Water.—When the density of the vapour of water is known, the increase of volume which occurs when a given quantity of water passes into the state of vapour may easily be calculated. Suppose, for instance, that we wish to find the volume which a cubic centimetre of water at 4° will occupy in the state of vapour at 100°. At this temperature the tension of the vapour is equal to one atmosphere, and its weight is equal to ·622 times the weight of the same volume of air at the same temperature and pressure. If then V be the volume in litres, we have (in grammes)

$$V \times 1{\cdot}293 \times \frac{1}{1+100a} \times {\cdot}622 = 1,$$

whence

$$V = \frac{1+100a}{1{\cdot}293 \times {\cdot}622} = \frac{1{\cdot}366}{{\cdot}804246} = 1{\cdot}698 \text{ lit.} = 1698 \text{ cubic centimetres.}$$

Hence we see that water at 4° gives about 1700 times its volume of vapour at 100° C.

The latent heat of evaporation is doubtless connected with this increase of volume; and it may be remarked that both these elements appear to be greater for water than for any other substance.

---

[1] Water is composed of 2 volumes of hydrogen, and 1 volume of oxygen, forming 2 volumes of vapour of water. The sum of the density of oxygen and twice the density of hydrogen is 1·244, and the half of this is exactly ·622.—*D.*

CHAPTER XXVIII.

HYGROMETRY.

285. Humidity.—The condition of the air as regards moisture involves two distinct elements: (1) the amount of vapour present in the air, and (2) the ratio of this to the amount which would saturate the air at the actual temperature. It is upon the second of these elements that our sensations of dryness and moisture chiefly depend, and it is this element which meteorologists have agreed to denote by the term *humidity;* or, as it is sometimes called, *relative humidity*. It is usually expressed as a percentage; for example, if the weight of vapour present is seven-tenths of that required for saturation, the humidity is said to be 70.

The words *humid* and *moist*, as applied to air in ordinary language, nearly correspond to this technical use of the word *humidity;* and air is usually said to be dry when its *humidity* is considerably below the average. In treatises on physics, "dry air" usually denotes air whose humidity is zero.

The air in a room heated by a hot stove contains as much vapour weight for weight as the open air outside; but it is drier, because its capacity for vapour is greater. In like manner the air is drier at noon than at midnight, though the amount of vapour present is about the same; and it is for the most part drier in summer than in winter, though the amount of vapour present is much greater.

Bearing in mind that a cubic foot of air is able to take up the same amount of vapour as a cubic foot of empty space, we may define the *humidity of the air* as *the weight of aqueous vapour in a given volume of air, expressed as a percentage of the weight of vapour at saturation which would occupy the same volume at the actual temperature.*

Also, since aqueous vapour nearly fulfils Boyle's law, the humidity of the air may be obtained by comparing the *tension* of the vapour present in the air with the *maximum tension* for the actual temperature.

286. Dew-point.—When air containing aqueous vapour is gradually cooled at constant pressure, its density increases, and the rate of increase is sensibly the same for the vapour as for the dry air with which it is mixed (inasmuch as vapours not in contact with their liquids nearly fulfil Gay-Lussac's law), until a point is reached at which the density of the vapour becomes equal to the maximum density corresponding to the temperature. This temperature is called the *dew-point* of the given mass, and any further reduction of temperature will be accompanied by the condensation of a portion of the vapour, which will take the form of dew, rain, snow, or hoar-frost, according to circumstances. If the cooling is produced by the low temperature of the sides of the containing vessel, the deposit will be dew or hoar-frost, according as the temperature of the sides is above or below the freezing-point. If the cooling takes place in the interior of the mass of air, the deposit will be rain or snow, according as the temperature of deposition is above or below the freezing-point.

In the operation of cooling down to the dew-point, the density of the vapour, as we have seen, increases. Let t denote the initial temperature, and T the dew-point, and let d and D be the densities of the vapour at these temperatures. Then we have, by Gay-Lussac's law,

$$D = d \cdot \frac{1 + at}{1 + aT}$$

But the *tension* of the vapour *is not sensibly changed* by the operation, since the whole pressure is by hypothesis preserved constant, and the changes of temperature and volume affect the dry and the vaporous constituent nearly alike.

If the reduction of temperature from t to T took place *at constant volume* (in a closed receiver, for example), we should then have

$$P = p \cdot \frac{1 + aT}{1 + at},$$

p and P denoting the vapour-tensions at the temperatures t and T; and the density would remain constant, since no vapour enters or escapes. In this case the vapour would not begin to be condensed till a somewhat lower temperature had been attained.

287. Hygroscopes.—Anything which serves to give rough indications of the state of the air as regards moisture may be called a *hygroscope* (ὑγρος, moist). Many substances, especially those which are composed of organic tissue, have the property of absorbing the moisture of the surrounding air, until they attain a condition of equilibrium, such that their affinity for the moisture absorbed is exactly equal to the force with which the latter tends to evaporate. Hence it follows that, according to the dampness or dryness of the air, such a substance will absorb or give up vapour, either of which processes is always attended with a variation in the dimensions of the body. The nature of this variation depends upon the peculiar structure of the substance; thus, for instance, bodies formed of filaments exhibit a greater increase in the direction of their breadth than of their length. Membranous bodies, on the other hand, such as paper or parchment, formed by an interlacing of fibres in all directions, expand or contract almost as if they were homogeneous. Bodies composed of twisted fibres, as ropes and strings, swell under the action of moisture, grow shorter, and are more tightly twisted. The opposite is the case with catgut, which is often employed in popular hygroscopes.

288. Hygrometers.—Instruments intended for furnishing precise measurements of the state of the air as regards moisture are called *hygrometers*. They may be divided into four classes:—

1. Hygrometers of absorption, which should rather be called hygroscopes.
2. Hygrometers of condensation, or dew-point instruments.
3. Hygrometers of evaporation, or wet and dry bulb thermometers.
4. Chemical hygrometers, for directly measuring the weight of vapour in a given volume of air.

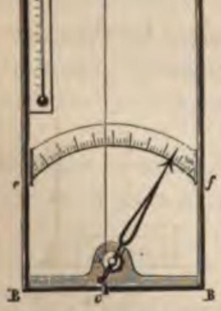


Fig. 266.
De Saussure's Hygroscope.

289. De Saussure's Hygrometer.—The best hygrometer of absorption is that of De Saussure, consisting of a hair deprived of grease, which by its contractions moves a needle (Fig. 266). When the hair relaxes, the needle is caused to move in the opposite direction by a weight, which serves to keep the hair always equally tight. The hair contracts as the humidity increases, but not in simple proportion, and Regnault's investigations have shown that, unless the most minute precautions are adopted in the construction and graduation of each individual instrument, this hygrometer will not furnish definite numerical measures.

Fig. 267 represents Monnier's modification of De Saussure's hygrometer, in which the hair, after passing over four pulleys, is attached to a light spring, which serves instead of a weight, and gives the advantage of portability.

These instruments are never employed for scientific purposes in this country.

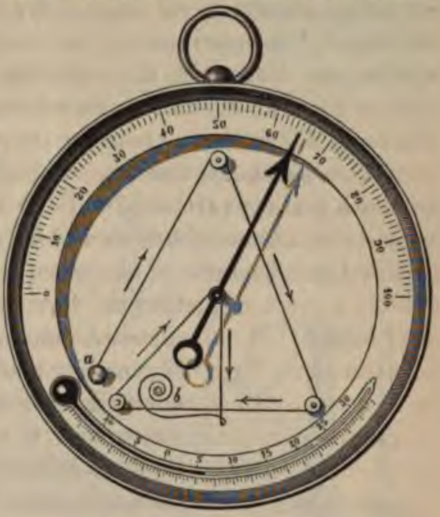


Fig. 267.—Monnier's Hygroscope.

290. Dew-point Hygrometers.—These are instruments for the direct observation of the dew-point, by causing moisture to be condensed from the air upon the surface of a body artificially cooled to a known temperature.

The dew-point, which is itself an important element, gives directly, as we have seen in § 286, the tension of vapour; and if the temperature of the air is at the same time observed, the tension requisite for saturation is known. The ratio of the former to the latter determines the humidity.

The principle of these instruments may be illustrated by a description of their simplest type, the hygrometer of Leroy, a French philosopher of the last century.

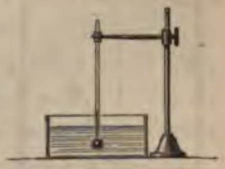


Fig. 268.
Leroy's Hygrometer.

291. Leroy's Hygrometer.—The instrument consists of a tin vessel containing water, in which a thermometer is immersed. The temperature of the water and containing vessel is gradually lowered by the introduction of ice, and when it has fallen below the dew-point of the adjacent air, a portion of the vapour will be condensed as dew upon the exterior of the vessel. This is at once recognized by the metallic surface losing its brilliancy.

We may observe that the deposition of dew does not begin till the point of saturation has been passed, and that the indication of the thermometer is consequently somewhat too low. Leroy proposed an empirical correction of half a degree. There are, however, other defects in the instrument; the use of ice does not afford a speedy and regular diminution of temperature; and it is especially objectionable to place an open vessel containing water in the very place where the humidity of the air is to be determined.

292. Daniell's Hygrometer.—Daniell's hygrometer is an instrument of much greater precision, and has been very extensively used. It consists of a bent tube with a globe at each end, and is partly filled with ether. The rest of the space is occupied with vapour of ether, the air having been expelled. One of the globes A contains a thermometer *t*. This globe is generally made of black glass, which presents a brilliant surface. The method of using the instrument is as follows:—The whole of the liquid is first passed into the globe A, and then the other globe B, which is covered with muslin, is moistened externally with ether. The evaporation of this ether from the muslin causes a partial condensation of vapour of ether in the interior of the globe, which produces a fresh evaporation from the surface of the liquid in A, thus lowering the temperature of that part of the instrument. By carefully watching the surface of the globe, the exact moment of the deposition of dew may be ascertained. The temperature is then read on the inclosed thermometer. This temperature is a little lower than the dew-point.

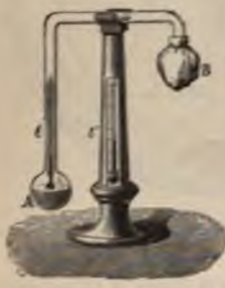


Fig. 269.
Daniell's Hygrometer.

If the instrument be now left to itself, the exact moment of the disappearance of the dew may be observed; this corresponds to an indicated temperature a little above the dew-point, and the usual plan is to take the mean between this temperature and that first observed. The temperature of the surrounding air is given by a thermometer *t'* attached to the stand.

Daniell's hygrometer, though capable of furnishing accurate indications, has some defects, which have been removed by the improvements effected by Regnault.

293. Regnault's Hygrometer.—Regnault's hygrometer consists (Fig. 270) of a glass tube closed at the bottom by a very thin silver cap D. The opening at the upper end is closed by a cork, through which passes the stem of a thermometer T, and a glass tube *t* open at both ends. The lower end of the tube and the bulb of the thermometer dip into ether contained in the silver cap. A side tube establishes communication between this part of the apparatus and a vertical tube U V, which is itself connected with an aspirator[1] A, placed at a convenient distance. By allowing the water in the aspirator to escape, a current of air is produced through the ether, which has the effect of keeping the liquid in agitation, and thus producing uniformity of temperature throughout the whole. It also tends to hasten evaporation; and the cold thus produced speedily causes a deposition of dew, which is observed from a distance with a telescope, thus obviating the risk of vitiating the observation by the too close proximity of the observer. The observation is facilitated by the contrast offered by the appearance of the second cap, which has no communication with the first, and contains a thermometer for giving the temperature of the external air. By regulating the flow of liquid from the aspirator, the temperature of the ether can be very nicely controlled, and the dew can be made to appear and disappear at temperatures nearly identical. The mean of the two will then very accurately represent the dew-point.

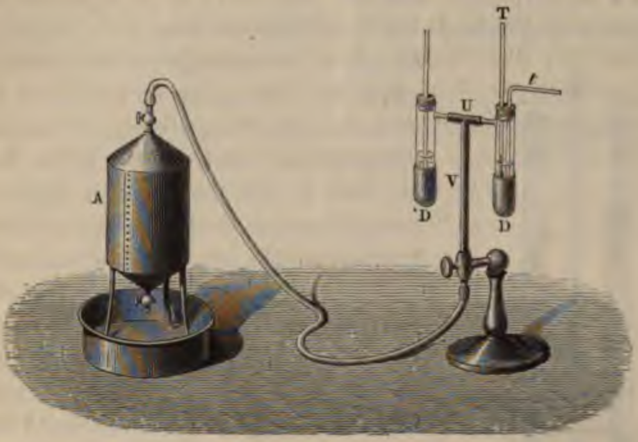


Fig. 270.—Regnault's Hygrometer.

The liquid employed in Regnault's hygrometer need not be ether.

---

[1] An aspirator is a vessel into which air is sucked at the top to supply the place of water which is allowed to escape at the bottom; or, more generally, it is any apparatus for sucking in air or gas.

Alcohol, a much less volatile liquid, will suffice. This is an important advantage; for, since the boiling-point of ether is 36° C. (97° F.), it is not easy to preserve it in hot climates.

294. Wet and Dry Bulb Hygrometer.—This instrument, which is also called Mason's hygrometer, and is known on the Continent as August's psychrometer, consists (Fig. 271) of two precisely similar thermometers, mounted at a short distance from each other, the bulb of one of them being covered with muslin, which is kept moist by means of a cotton wick leading from a vessel of water. The evaporation which takes place from the moistened bulb produces a depression of temperature, so that this thermometer reads lower than the other by an amount which increases with the dryness of the air. The instrument must be mounted in such a way that the air can circulate very freely around the wet bulb; and the vessel containing the water should be small, and should be placed some inches to the side. The level of this vessel must be high enough to furnish a supply of water which keeps the muslin thoroughly moist, but not high enough to cause a drop to form at the bottom of the bulb. Unless these precautions are observed, the depression of temperature will not be sufficiently great, especially in calm weather.

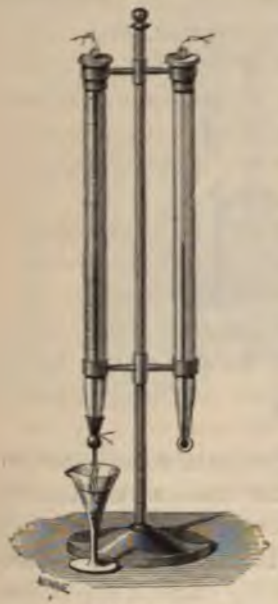


Fig. 271.
Wet and Dry Thermometers.

In frosty weather the wick ceases to act, and the bulb must be dipped in water some time before taking an observation, so that all the water on the bulb may be frozen, and a little time allowed for evaporation from the ice before the reading is taken.

The great facility of observation afforded by this instrument has brought it into general use, to the practical exclusion of other forms of hygrometer. As the theoretical relation between the indications of its two thermometers and the humidity as well as the dew-point of the air is rather complex, and can scarcely be said to be known with certainty, it is usual, at least in this country, to effect the reduction by means of tables which have been empirically constructed by comparison with the indications of a dew-point instrument. The tables universally employed by British observers were constructed by Mr. Glaisher, and are based upon a comparison of the simultaneous readings of the wet and dry bulb thermometers and of Daniell's hygrometer taken for a long series of years at Greenwich observatory, combined with some similar observations taken in India and at Toronto.[1]

According to these tables, the difference between the dew-point and the wet-bulb reading bears a constant ratio to the difference between the two thermometers, when the temperature of the dry-bulb thermometer is given. When this temperature is 53° F., the dew-point is as much below the wet-bulb as the wet-bulb is below the temperature of the air. At higher temperatures the wet-bulb reading is nearer to the dew-point than to the air-temperature, and the reverse is the case at temperatures below 53°.

In order to obtain a clue to the construction of a rational formula for deducing the dew-point from the indications of this instrument, we shall assume that the wet-bulb is so placed that its temperature is not sensibly affected by radiation from surrounding objects, and hence that the heat which becomes latent by the evaporation from its surface is all supplied by the surrounding air. When the temperature of the wet-bulb is falling, heat is being consumed by evaporation faster than it is supplied by the air; and the reverse is the case when it is rising. It will suffice to consider the case when it is stationary, and when, consequently, the heat consumed by evaporation in a given time is exactly equal to that supplied by the air.

Let t denote the temperature of the air, which is indicated by the dry-bulb thermometer; t' the temperature of the wet-bulb; T the temperature of the dew-point, and let f, f', F be the vapour-tensions corresponding to saturation at these three temperatures. Then, as shown in § 286, the tension of the vapour present in the air at its actual temperature t is also equal to F.

We shall suppose that wind is blowing, so that continually fresh portions of air come within the sphere of action of the wet-bulb. Then each particle of this air experiences a depression of temperature and an increase of vapour-tension as it comes near the wet-bulb, from both of which it afterwards recovers as it moves away and mixes with the general atmosphere.

---

[1] The first edition of these Tables differs considerably from the rest, and is never used; but there has been no material alteration since the second edition (1856).

If now it is legitimate to assume[1] that this depression of temperature and exaltation of vapour-tension are always proportional to one another, not only in comparing one particle with itself at different times, but also in comparing one particle with another, we have the means of solving our problem; at all events, if we may make the additional assumptions that a portion of the air close to the wet-bulb is at the temperature of the wet-bulb, and is saturated.

On these assumptions the greatest reduction of temperature of the air is $t-t'$, and the greatest increase of vapour-tension is $f'-\mathrm{F}$, and the corresponding changes in the whole mass are proportional to these. The three temperatures t, t', T must therefore be so related, that the heat lost by a mass of air in cooling through the range $t-t'$, is just equal to the heat which becomes latent in the formation of as much vapour as would raise the vapour-tension of the mass by the amount $f'-\mathrm{F}$.

Let h denote the height of the barometer, s the specific heat of air (Chap. xxxi.), D the relative density of vapour (§ 278 A.), L the latent heat of steam.

Then the mass of the air is to that of the vapour required to produce the additional tension, as h to $\mathrm{D}\,(f'-\mathrm{F})$, and we are to have

$$\mathrm{LD}\,(f'-\mathrm{F}) = s\,(t-t')\,h,$$

or

$$f'-\mathrm{F} = (t-t')\,h \cdot \frac{s}{\mathrm{LD}}, \qquad (1)$$

which is the required formula, enabling us, with the aid of a table of vapour-tensions, to determine F, and therefore the dew-point T, when the temperatures t, t' of the dry and wet bulb, and the height h of the barometer, have been observed. The expression for the relative humidity will be $\frac{\mathrm{F}}{f}\,100$.

Properly speaking, s denotes the specific heat not of dry air but of air containing the actual amount of vapour, and therefore depends to some extent upon the very element which is to be determined; but its variation is inconsiderable. L also varies with the known quantity t', but its variations are also small within the limits which occur in practice. The factor $\frac{s}{\mathrm{LD}}$ may therefore be regarded as constant, and its value, as adopted by Dr. Apjohn for the Fahrenheit scale, is $\frac{1}{2610}$ or $\frac{1}{30} \times \frac{1}{87}$. We thus obtain what is known as *Apjohn's formula*,

---

[1] The assumption which Dr. Apjohn actually makes is as follows:—"When in the moist-bulb hygrometer the stationary temperature is attained, the caloric which vaporizes the water is necessarily exactly equal to that which the air imparts in descending from the temperature of the atmosphere to that of the moistened bulb; and the air which has undergone this reduction becomes saturated with moisture" (*Trans. R.I.A.* Nov. 1834).

This implies that unless air passes near enough to the wet-bulb to become completely saturated, it experiences no depression of temperature whatever—a very harsh supposition; but August independently makes the same assumption.

$$\mathrm{F} = f' - \frac{t - t'}{87} \cdot \frac{h}{30}. \qquad (2)$$

When the wet-bulb is frozen, L denotes the sum of the latent heats of liquefaction and vaporization, and the formula becomes

$$\mathrm{F} = f' - \frac{t \quad t'}{96} \cdot \frac{h}{30}. \qquad (3)$$

In calm weather, and also in very dry weather, the humidity, as deduced from observations of wet and dry thermometers, is generally too great, probably owing mainly to the radiation from surrounding objects on the wet-bulb, which makes its temperature too high.

295. Chemical Hygrometer.—The determination of the quantity of aqueous vapour in the atmosphere may be effected by ordinary chemical analysis in the following manner:—

An aspirator A, of the capacity of about 50 litres, communicates at its upper end with a system of U-tubes 1, 2, 3, 4, 5, 6, filled with pieces of pumice soaked in sulphuric acid. The aspirator being full of water, the stop-cock at the bottom is opened, and the air which

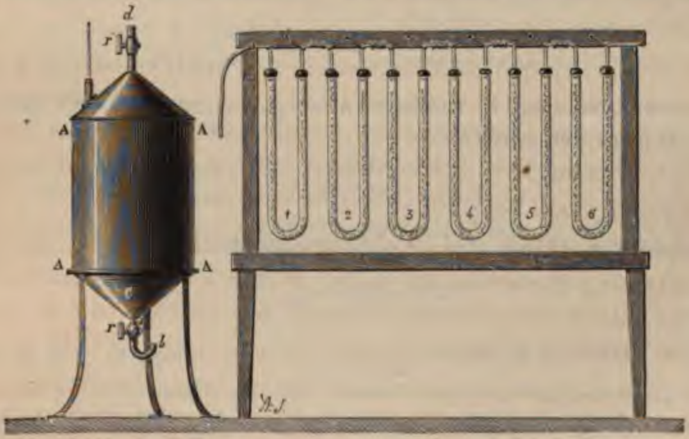


Fig. 272.—Chemical Hygrometer.

enters the aspirator to take the place of the water is obliged to pass through the tubes, where it leaves all its moisture behind. This moisture is deposited in the first tubes only. The last tube is intended to absorb any moisture that may come from the aspirator. Suppose w to be the increase of weight of the first tubes 4, 5, 6; this is evidently the weight of the aqueous vapour contained in the air which has passed through the apparatus. The volume V of this air, which we will suppose to be expressed in litres, may easily be found by measuring the amount of water which has escaped. This air has been again saturated by contact with the water of the aspirator, and the aqueous vapour contained in it is consequently at the maximum tension corresponding to the temperature indicated by a thermometer attached to the apparatus. Let this tension be denoted by f. The volume occupied by this air when in the atmosphere, where the temperature is T, is known by the regular formulæ to have been

$$\mathrm{V} \cdot \frac{\mathrm{H}-f}{\mathrm{H}-x} \cdot \frac{1+a\mathrm{T}}{1+at},$$

x denoting the tension of the aqueous vapour in the atmosphere, and H the total atmospheric pressure as indicated by the barometer; and, since the relative density of steam is ·622, and the weight of a litre of air at temperature 0° C. and pressure 760 mm. is 1·293 gramme, the weight of vapour which this air contained must have been

$$\mathrm{V} \cdot \frac{\mathrm{H}-f}{\mathrm{H}-x} \cdot \frac{1+a\mathrm{T}}{1+at} \times 1{\cdot}293 \times {\cdot}622 \cdot \frac{x}{760} \cdot \frac{1}{1+a\mathrm{T}},$$

which must be equal to the known weight w, and thus we have an equation from which we find

$$x = \frac{w\,(1+at)\,760\,\mathrm{H}}{\mathrm{V}\,(\mathrm{H}-f) \times {\cdot}622 \times 1{\cdot}293 + w\,(1+at)\,760}.$$

A good approximation will be obtained by writing

$$w = \mathrm{V} \times 1{\cdot}293 \times {\cdot}622\,\frac{x}{760},$$

whence

$$x = 945\,\frac{w}{\mathrm{V}}.$$

This method has all the exactness of a regular chemical analysis, but it involves great labour, and is, besides, incapable of showing the sudden variations which often occur in the humidity of the atmosphere. It can only give the mean quantity of moisture in a given volume of air during the time occupied by the experiment.

Its accuracy, however, renders it peculiarly suitable for checking the results obtained by other methods.

296. Weight of a given Volume of Moist Air.—The laws of vapours and the known formulæ of expansion enable us to solve a problem of very frequent occurrence, namely, the determination of the weight of a given volume of moist air. Let V denote the volume of this air, H its pressure, f the tension of the vapour of water in it, and t its temperature. The entire gaseous mass may be divided into two parts, a volume V of dry air at the temperature t and the pressure $H-f$, whose weight is, by the known formulæ,

$$V \times 1{\cdot}293 \times \frac{1}{1+at} \cdot \frac{H-f}{760},$$

and a volume V of aqueous vapour at the temperature t and the pressure f; the weight of this latter is

$$\frac{5}{8} V \times 1{\cdot}293 \times \frac{1}{1+at} \cdot \frac{f}{760}.$$

The sum of these two weights is the weight required, viz.

$$V \times 1{\cdot}293 \times \frac{1}{1+at} \cdot \frac{H-\frac{3}{8}f}{760}.$$

297. Ratio of the Volumes occupied by the same Air when saturated at Different Temperatures and Pressures.—Suppose a mass of air to be in presence of a quantity of water which keeps it always saturated; let H be the total pressure of the saturated air, t its temperature, and V its volume.

At a different temperature and pressure t' and H', the volume occupied V' will in general be different. The two quantities V and V' may be considered as the volumes occupied by a mass of dry air at temperatures t and t' and pressures $H-f$ and $H'-f'$; we have then (§ 201) the relation

$$\frac{V}{V'} = \frac{H'-f'}{H-f} \cdot \frac{1+at}{1+at'} \qquad (1)$$

In passing from one condition of temperature and pressure to another, it may be necessary, for the maintenance of saturation, that a new quantity of vapour should be formed, or that a portion of the vapour should be condensed, or again, neither the one nor the other change may take place. To investigate the conditions on which these alternatives depend, let D and D' be the maximum densities of vapour at the temperatures t and t' respectively. Suppose we have $t' > t$, and that, without altering the pressure f, the temperature of the vapour is raised to t', all contact with the generating liquid being prevented. The vapour will no longer remain saturated; but, on increasing the pressure to f', keeping the temperature unchanged, saturation will again be produced. This latter change does not alter the actual quantity of vapour, and if we suppose its coefficient of expansion to be the same as that of air, we shall have (§ 201)

$$\frac{D}{D'}=\frac{f}{f'}\cdot\frac{1+\alpha t'}{1+\alpha t}, \qquad (2)$$

and, by multiplying together equations (1) and (2), we have

$$\frac{VD}{V'D'}=\frac{H'f-ff'}{Hf'-ff'}. \qquad (3)$$

From this result the following particular conclusions may be deduced:—

1. If $H'f=Hf'$, $VD=V'D'$, that is, the mass of vapour is the same in both cases; consequently, neither condensation nor evaporation takes place.

2. If $H'f>Hf'$, $VD>V'D'$, that is, partial condensation occurs.

3. If $H'f<Hf'$, $VD<V'D'$, that is, a fresh quantity of vapour is required to maintain saturation. In this case the formula (1) can only be applied when we are sure that there is a sufficient excess of liquid to produce the fresh quantity of vapour which is required.

The general formulæ (1), (2), (3) furnish the solution of many particular problems which may be proposed by selecting some one of the variables for the unknown quantity.

298. Aqueous Meteors.—The name *meteor*, from the Greek μετεωρος, *aloft*, though more especially applied to the bright objects otherwise called shooting-stars and their like, likewise includes all the various phenomena which have their seat in the atmosphere; for example, clouds, rain, and lightning. This use of the word *meteor* is indeed somewhat rare; but the correlative term *meteorology* is invariably employed to denote the science which treats of these phenomena, in fact, the *science of matters pertaining to weather.*

By *aqueous meteors* are to be understood the phenomena which result from the condensation of aqueous vapour contained in the air, such as rain, dew, and fog. This condensation may occur in either of two ways. Sometimes it is caused by the presence of a cold body, which reduces the film of air in contact with it to a temperature below the dew-point, and thus produces the liquefaction or solidification of a portion of its vapour in the form of dew or hoar-frost. The circumstances connected with the formation of dew will be treated in Chapter xxix. All that we need remark now is that it essentially consists in the deposition of moisture on the very body whose low temperature causes the condensation.

When, on the contrary, the condensation of vapour takes place in the interior of a large mass of air, the resulting liquid or solid *falls* in obedience to gravity. This is the origin of rain and snow.

299. Cloud and Mist.—When vapour is condensed in the midst of the air, the first product is usually *mist* or *cloud*, a cloud being merely a mist at a great elevation in the air.

Natural clouds are similar in constitution to the cloudy substance which passes off from the surface of hot water, or which escapes in puffs from the chimney of a locomotive. In common language this substance is often called steam or vapour, but improperly, for steam is, like air, transparent and invisible, and the appearance in question is produced by the presence of particles of liquid water, which have been formed from vapour by cooling it below its dew-point.

Naturalists are not agreed as to the nature of these particles, the difference of opinion having arisen in the attempt to explain their suspension in the atmosphere. Some have endeavoured to account for it by maintaining that they are hollow;[1] but even if we could conceive of any causes likely to lead to the formation of such bubbles, it would furnish no solution of the difficulty, for the air inclosed in a bubble is no rarer, but in fact denser, than the external air (§ 97 B); the bubble and its contents are therefore heavier than the air which it displaces.

It is more probable that the particles are solid spheres differing only in size from rain-drops. It has been urged against this view, that such drops ought to exhibit rainbows, and the objection must be allowed to have some weight. The answer to it is probably to be found in the excessive smallness of the globules. Indeed, the non-occurrence of bows may fairly be alleged as proving that the diameters of the drops are comparable with the lengths of waves of light.

This smallness of the particles is amply sufficient to explain all the observed facts of cloud suspension, without resorting to any special theory. It probably depends on the same principle as the suspension of the motes which are rendered visible when a beam of sunlight traverses a darkened room. It is true that these motes, which are small particles of matter of the most various kinds, are never seen resting stationary in the air; but neither are the particles which compose clouds. All who have ever found themselves in mountain mists must have observed the excessive mobility of their constituent parts, which yield to the least breath of wind, and are carried about by it like the finest dust. Sometimes, indeed, clouds have the *appearance* of being fixed in shape and position; but this is an illusion due to distance which renders small movements invisible. In many cases, the fixity is one of form and not of material; for example, the permanent cloud on a mountain-top often consists of successive portions of air, which become cloudy by condensation as they pass through the cold region at the top of the mountain, and recover their transparency as they pass away.

---

[1] Those who adopt this view call them *vesicles* (*vesica*, a bladder), and call mist or cloud *vapour in the vesicular state.*

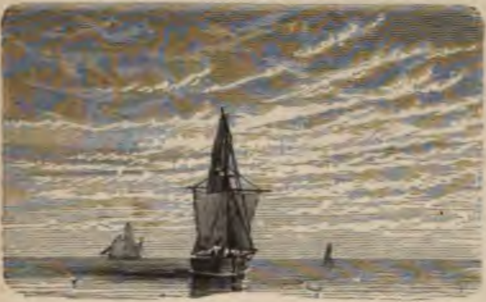


Fig. 273.—Cirrus.

300. Varieties of Cloud.—The cloud nomenclature generally adopted by meteorologists was devised by Howard, and is contained in his work on the climate of London. The fundamental forms, according to him, are three—*cirrus*, *cumulus*, and *stratus*.

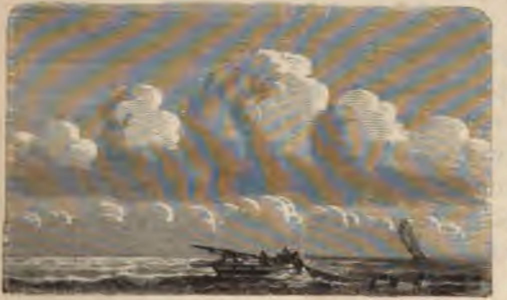


Fig. 274.—Cumulus.

1. *Cirrus* consists of fibrous, wispy, or feathery clouds, occupying the highest region of the atmosphere. The name *mare's-tails*, which is given them by sailors, describes their aspect well. They are higher than the greatest elevations attained by balloons, and are probably composed of particles of ice. It is in this species of cloud, and its derivatives, that haloes are usually

seen; and their observed forms and dimensions seem to agree with the supposition that they are formed by refractions and reflections from ice-crystals.

2. *Cumulus* consists of rounded masses, convex above and comparatively flat below. Their form bears a strong resemblance to heaps of cotton wool, hence the names *balls of cotton* and *wool-packs* applied to these clouds by sailors. They are especially prevalent in summer, and are probably formed by columns of ascending vapour which become condensed at their upper extremities.

3. *Stratus* consists of horizontal sheets. Its situation is low in the atmosphere, and its formation is probably due to the cooling of the earth and the lower portion of the air by radiation. It is very frequently formed at sunset, and disappears at sunrise.

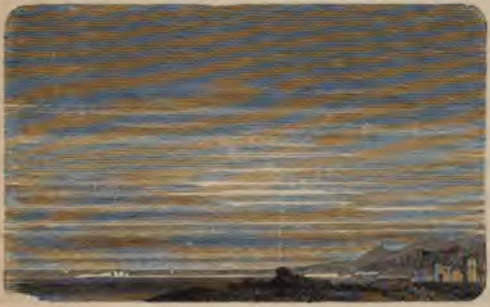


Fig. 275.—Stratus.

Of the intermediate forms it may suffice to mention *cirro-cumulus,* which floats at a higher level than cumulus, and consists usually of small roundish masses disposed with some degree of regularity. This is the cloud which forms what is known as a *mackerel sky.*

As a distinct form not included in Howard's classification, may be mentioned *scud,* the characteristic of which is that, from its low elevation, it *appears* to move with excessive rapidity.

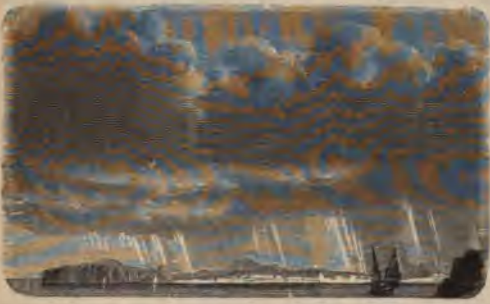


Fig. 276.—Nimbus.

Howard gives the name of *nimbus* to any cloud which is discharging rain; and, for no very obvious reason, he regards this rain-cloud as compounded of (or intermediate between) the three elementary types above defined.

The classification of clouds is a subject which scarcely admits of precise treatment; the varieties are so endless, and they shade so gradually into one another.

301. Causes of the Formation of Cloud and Mist.—Since clouds are merely condensed vapour, their formation is regulated by the causes which tend to convert vapour into liquid. Such liquefaction implies the presence of a quantity of vapour greater than that which, at the actual temperature, would be sufficient for saturation, a condition of things which may be brought about by the cooling of a mass of moist air in any of the following ways:—

(1.) By radiation from the mass of air to the cold sky.

(2.) By the neighbourhood of cold ground, for example, mountain-tops.

(3.) By the cooling effect of expansion, when the mass of air ascends into regions of diminished pressure. This cooling of the ascending mass is accompanied by a corresponding warming of the air which descends, it may be in some distant locality, to supply its place.

Causes (2) and (3) combine to produce the excessive rainfall which generally characterizes mountainous districts.[1]

It is believed that waterspouts are produced by the rapid ascent of a stream of air up the axis of an aerial vortex.

(4.) By the contact and mixture of cooler air.[2] It is obvious, however, that this cooler air must itself be warmed by the process; and as both the temperature and vapour-density of the mixture will be intermediate between those of the two components, it does not obviously follow (as is too often hastily assumed) that such contact tends to produce precipitation. Such is however the fact, and it depends upon the principle that the density of saturation increases faster than the temperature; or, what is the same thing, that the curve in which temperature is the abscissa and maximum vapour-density the ordinate, is everywhere concave upwards.

It will be sufficient to consider the case of the mixing of two equal volumes of saturated air at different temperatures, which we will denote by t_1 and t_2. Let the ordinates AA', BB' represent the densities of vapour for saturation at these temperatures, $A'mB'$ being the intermediate portion of the curve, and Cm the ordinate at the middle point of AB, representing therefore the density of saturation for the temperature $\frac{1}{2}(t_1+t_2)$. When the equal volumes are mixed, since the colder *mass* is slightly the greater, the temperature of the mixture will be something less than $\frac{1}{2}(t_1+t_2)$, and, if there were no condensation of vapour, the density of vapour in the mixture would be $\frac{1}{2}(AA'+BB') = Cn$. But the density for saturation is something less than Cm. The excess of vapour is therefore represented by something more than mn. The amount actually precipitated will, however, be less than this, since the portion which is condensed gives out its latent heat, and thus contributes to keep up the temperature of the whole.

---

[1] The rainiest place at present known in Great Britain is about a mile south of Seathwaite in Cumberland, where the annual rainfall is about 165 inches. The rainiest place in the world is believed to be Cherra Ponjee, in the Khasyah Mountains, about 300 miles N.E. of Calcutta, where the annual fall is about 610 inches.

[2] Contact with cooler air may be regarded as equivalent to mixing; for vapour diffuses rapidly.

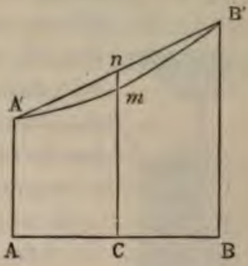


Fig. 276 A.

The cause here indicated combines with (3) to produce condensation when masses of air ascend.

On the surface of the earth mists are especially frequent in the morning and evening; in the latter case extending over all the surface; in the former principally over rivers and lakes. The mists of evening are due simply to the rapid cooling of the air after the heat of the sun has been withdrawn. In the morning another cause is at work. The great specific heat of water causes it to cool much more slowly than the air, so that the vapour rising from a body of water enters into a colder medium, and is there partly condensed, forming a mist, which, however, confines itself to the vicinity of the water, and is soon dissipated by the heat of the rising sun.

302. Rain.—In what we have stated regarding the constitution of clouds, it is implied that clouds are always raining, since the drops of which they are composed always tend to obey the action of gravity. But, inasmuch as there is usually a non-saturated region intervening between the clouds and the surface of the earth, these drops, when very small, are usually evaporated before they have time to reach the ground. Ordinary rain-drops are formed by the coalescing of a number of these smaller particles.

By the amount of annual rainfall at a given place is meant the depth of water that would be obtained if all the rain which falls there in a year were collected into one horizontal sheet; and the depth of rain that falls in any given shower is similarly reckoned.

It is the depth of the pool which would be formed if the ground were perfectly horizontal, and none of the water could get away. The instrument employed for determining it is called a *rain-gauge*. It has various forms, one of which is represented in the adjoining figure. B is a funnel into which the rain falls, and from which it trickles into the reservoir A. It is drawn off by means of the stop-cock *r*, and measured in a graduated glass, each division of which corresponds to $\frac{1}{100}$ of an inch of rain.[1]

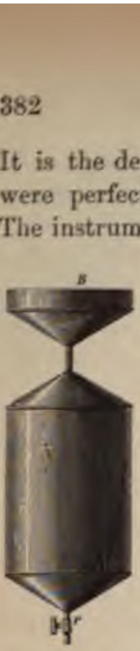


Fig. 277.
Rain-gauge.

It is essential that the receiving surface—the top of the funnel—should be truly horizontal, otherwise the gauge will catch too much or too little according to the direction of the wind.

The best place for a rain-gauge is the centre of a level and open plot; and the height of its receiving surface should be not less than 6 inches, to avoid in-splashing. The roof of a house is a bad place on account of the eddies which abound there.

A circumstance which has not yet been fully explained is that the higher a gauge is above the ground the less rain it catches. In the case of gauges on the top of poles in an open situation, the amount collected is diminished by $\frac{1}{10}$th part of itself by doubling the height of the receiving surface, as shown by comparing gauges in the same plot of ground at heights ranging from 6 inches to 20 feet.[2]

By means of tipping-buckets and other arrangements, automatic records of rainfall are obtained at the principal observatories. The best of these pluviometers is Osler's, which, by means of spiral springs stretched by the weight of the water, furnishes a continuous record, until a quarter of an inch has been collected, when the reservoir empties itself, and a fresh record begins.

The mean annual rainfall, according to Mr. Symons, is 20 inches at Lincoln and Stamford; 21 at Aylesbury, Bedford, and Witham; 24 at London and Edinburgh; 30 at Dublin, Perth, and Salisbury; 33 at Exeter and Clifton; 35 to 36 at Liverpool and Manchester; 40 at Glasgow and Cork; 50 at Galway; 64 at Greenock and Inverary; 86 at Dartmoor; and 91 on Benlomond.

---

[1] The best work on the subject of rain and its measurement is the little treatise entitled *Rain* by Mr. G. J. Symons, a gentleman who devotes his life to the investigation of British rainfall. Mr. Symons would probably tell us that the funnel in the above figure is too flat, and would cause some of the rain to splash out.

[2] This appears from the table in Symons on *Rain*, p. 19.

303. Snow and Hail.—Snow is probably formed by the direct passage of vapour into the solid state. Snow-flakes, when examined under the microscope, are always found to be made up of elements possessing hexagonal symmetry. In Fig. 278 are depicted various forms observed by Captain Scoresby during a long sojourn in the Arctic regions.

In these cold countries the air is often filled with small crystals of ice which give rise to the phenomena of haloes and parhelia.

Hail is probably due to the freezing of rain-drops in their passage through strata of air colder than those in which they were formed. Even in fine summer weather, a freezing temperature exists at the height of from 10,000 to 20,000 feet, and it is no unusual thing for a colder stratum to underlie a warmer, although, as a general rule, the temperature diminishes in ascending.

CHAPTER XXIX.

RADIANT HEAT.

305. Radiation.—When two bodies at different temperatures are brought opposite to each other, an unequal exchange of heat takes place through the intervening distance; the temperature of the hotter body falls, while that of the colder rises, and after some time the temperature of both becomes the same. This propagation of heat across an intervening space is what is meant by *radiation*, and the heat transmitted under these conditions is called *radiant heat*. Instances of heat communicated by radiation are the heat of a fire received by a person sitting in front of it, and the heat which the earth receives from the sun.

This last instance shows us that radiation as a means of propagating heat is independent of any ponderable medium. But since the solar heat is accompanied by light, it might still be questioned whether dark heat could in the same way be propagated through a vacuum.

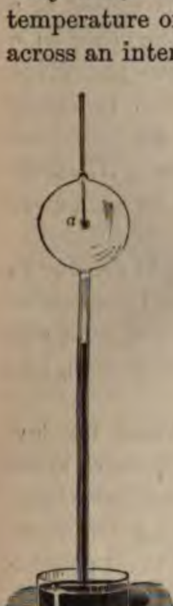


Fig. 279.—Rumford's Experiment.

This was tested by Rumford in the following way:—He constructed a barometer (Fig. 279), the upper part of which was expanded into a globe, and contained a thermometer hermetically sealed into a hole at the top of the globe, so that the bulb of the thermometer was at the centre of the globe. The globe was thus a Torricellian vacuum-chamber. By melting the tube with a blow-pipe, the globe was separated, and was then immersed in a vessel containing hot water, when the thermometer was immediately observed to rise to a temperature evidently higher than could be due to the conduction of heat through the stem. The heat had therefore been communicated by direct radiation through the vacuum between the sides of the globe and the bulb a of the thermometer.

306. Radiant Heat travels in Straight Lines.—In a uniform medium the radiation of heat takes place in straight lines. If, for instance, between a thermometer and a source of heat, there be placed a number of screens, each pierced with a hole, and if the screens be so arranged that a straight line can be drawn without interruption from the source to the thermometer, the temperature of the latter immediately rises; if a different arrangement be adopted, the heat is stopped by the screens, and the thermometer indicates no effect.

The heat which travels along any one straight line is called a ray of heat. Thus we say that rays of heat issue from all points of the surface of a heated body, or that such a body emits rays of heat.

Such language may be thought to imply the hypothesis that heat is a substance (caloric) which is accumulated in bodies, and emitted by them in all directions. A ray of heat would thus consist of a series of molecules of caloric issuing forth one after the other in a straight line. But, in fact, the definition which we have just given of a ray of heat is independent of any hypothesis, and is simply experimental; it amounts merely to the expression of the incontestable fact that the direction of radiation is rectilinear. Whatever idea we may form about the nature of heat, it must be such as to imply this rectilinear propagation.

It is now generally admitted that both heat and light are due to a vibratory motion which is transmitted through space by means of a fluid called ether. According to this theory the rays of light and heat are lines drawn in all directions from the origin of motion, and along which the vibratory movement advances.

307. Law of Cooling.—It is often important to know the law according to which a body cools when placed in an inclosure of lower temperature than its own; for we are thus enabled to take account of the heat which a body loses during the progress of an experiment. This law, when stated in such terms as to be applicable to all possible differences of temperature and all possible conditions of the surrounding medium, becomes exceedingly complex; but when the difference of temperature is small, amounting only to a few degrees, the law known as Newton's law of cooling can be applied without sensible error. It is this:—*the rate at which the body loses heat is proportional to the difference between the temperature of its surface and* *that of the inclosure.* If the body be of sensibly uniform temperature throughout its whole mass, as in the case of a vessel with thin metallic sides containing water which is kept stirred, or of the quicksilver in the bulb of a thermometer, the fall of temperature is proportional to the loss of heat, and Newton's law as applied to such a body asserts that *the rate at which the temperature falls is proportional to the excess of the temperature of the body above that of the inclosure.*

To test this law experimentally, we observe from time to time the excess of the temperature of a thermometer above that of the air in which it is cooling. It is found, that, if the observations are made at equal intervals of time, the observed excesses form a decreasing geometric series.

To express this fact algebraically, let θ_0 denote the initial excess of temperature, and $\frac{1}{m}$ the ratio of the series. Then the excess at the end of a unit of time will be $\frac{\theta_0}{m}$, at the end of two units $\frac{\theta_0}{m^2}$, and after t units $\frac{\theta_0}{m^t}$; so that if θ denote the excess at time t, we have

$$\theta = \frac{\theta_0}{m^t} = \theta_0 m^{-t}. \qquad (1)$$

One pair of observations is sufficient to determine the value of the constant m, which is different for different thermometers.

By *rate of cooling* is meant the *fall of temperature per unit time* which is taking place at the instant considered. This is computed approximately by dividing the fall of temperature in a small interval of time by the length of the interval. Its exact value is given by the differential calculus, and is

$$-\frac{d\theta}{dt} = \theta_0 m^{-t} \log_e m = \theta \log_e m, \qquad (2)$$

which is proportional to θ, as asserted by Newton's law

A precisely similar law holds for *warming.*

307A. Cooling by Radiation in Vacuo.—The cooling of a thermometer in air is effected partly by the contact of the air, and partly by radiation. When the thermometer is placed in the centre of a vacuous space, radiation alone can operate, namely, radiation from the thermometer to the walls of the inclosure. The law of cooling under these conditions has been investigated experimentally by Dulong and Petit, and was reduced by them to a formula which was found to be accurate within the limits of experimental error for all the ranges of temperature employed, the excess of the temperature of the thermometer above that of the walls of the inclosure ranging from 20° to 240° C. They found that the rate of cooling did not depend upon the difference of temperature alone, but was faster at high than at low temperatures; also that, for a given temperature of the walls, the rate of cooling was not simply proportional to the excess, but increased more rapidly. Both these results are expressed by their formula

$$V = ca^t (a^\theta - 1), \qquad (3)$$

where V denotes the rate of cooling, c and a constants, t the temperature of the walls of the inclosure, and θ the excess of temperature, so that $t+\theta$ is the temperature of the thermometer. If we denote this by t' the formula may be thrown into the more symmetrical form

$$V = c\,(a^{t'} - a^t), \qquad (4)$$

which suggests the idea that an unequal *exchange* of heat takes place between the thermometer and the walls, the thermometer giving to the walls a quantity of heat represented by $a^{t'}$, and receiving in exchange[1] only the quantity a^t. The former of these amounts remains the same at all temperatures of the inclosure, and the latter is the same for all temperatures of the thermometer.

When the temperatures are Centigrade, the constant a is 1·0077. When they are Fahrenheit it is 1·0043, the form of the expression for V being unaffected by a change of the zero from which the temperatures are reckoned. The value of c depends upon the size of the bulb and some other circumstances, and is changed by a change of zero.

By developing a^θ in ascending powers of θ, it will be found that formula (3) agrees sensibly with Newton's law when the excess of temperature does not exceed a few degrees.

308. Law of Inverse Squares.—If we take a delicate thermometer and place it at successively increasing distances from a source of heat, the temperature indicated by the instrument will exceed that of the atmosphere by decreasing amounts, showing that the intensity of radiant heat diminishes as the distance increases. The law of variation may be discovered by experiment. In fact, when the excess of temperature of the thermometer becomes fixed, we know that the heat received is equal to that lost by radiation; but this latter is, by Newton's law, proportional to the excess of temperature above that of the surrounding air; we may accordingly consider this excess as the measure of the heat received. It has been found, by experiments at different distances,[1] that the excess is inversely proportional to the square of the distance; we may therefore conclude that *the intensity of the heat received from any source of heat varies inversely as the square of the distance.*

---

[1] [illegible] to the *theory of exchanges*, the heat emitted by the thermometer is $ca^{t'}$ plus [illegible] depending on the zero of the temperature scale employed, and the heat [illegible] ca^t plus the same constant. It may be remarked that the factor c also [illegible] from which temperatures are reckoned as well as upon the length [illegible] a depends on the latter only.

The following experiment, devised by Tyndall, supplies another simple proof of this fundamental law:—

The thermometer employed is a Melloni's pile, the nature of which we shall explain in § 313. This is placed at the small end of a hollow cone, blackened inside, so as to prevent any reflection of heat from its inner surface. The pile is placed at S and S′ in front of a vessel filled with boiling water, and coated with lamp-black on the side next the pile. It will now be observed that the temperature indicated by the pile remains constant for all distances. This result proves the law of inverse squares. For the arrangement adopted prevents the pile from receiving more heat than that due to the area of AB in the first case, and to the area A′B′ in the second. These are the areas of two circles, whose radii are respectively proportional to SO and S′O; and the areas are consequently proportional to the

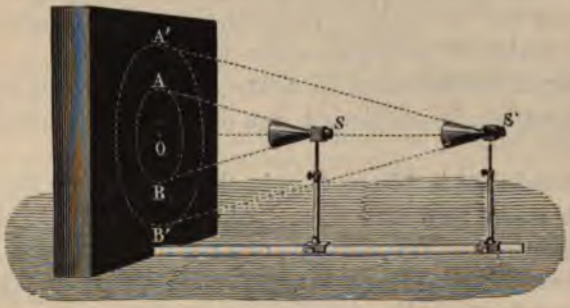


Fig. 280.—Law of Inverse Squares.

---

[1] The dimensions of the source of heat must be small in comparison with the distance of the thermometer, as otherwise the distances of different parts of the source of heat from the thermometer are sensibly different. In this case, the amount of heat received varies directly as the solid angle subtended by the source of heat.

squares of SO and S′O. Since, therefore, these two areas communicate the same quantity of heat to the pile, the intensity of radiation must vary inversely as the squares of the distances SO and S′O.

The law of inverse squares may also be established *a priori* in the following manner:—

Suppose a sphere of given radius to be described about a radiating particle as centre. The total heat emitted by the particle will be received by the sphere, and all points on the sphere will experience the same calorific effect. If now the radius of the sphere be doubled, the surface will be quadrupled, but the total amount of heat remains the same as before, namely, that emitted by the radiating particle. Hence we conclude that the quantity of heat absorbed by a given area on the surface of the large sphere is one-fourth of that absorbed by an equal area on the small sphere; which agrees with the law stated above.

This demonstration is valid, whether we suppose the radiation of heat to consist in the emission of matter or in the emission of energy; for energy as well as matter is indestructible, and remains unaltered in amount during its propagation through space.

309. Law of the Reflection of Heat.—When a ray of heat strikes a polished surface, it is reflected in a direction determined by fixed laws.

If at the point of incidence, that is, the point where the ray meets the surface, a line be drawn normal or perpendicular to the surface, the plane passing through this line and the incident ray is called the *plane of incidence*. With this explanation we proceed to give the laws of the reflection of heat:—

1. When a ray of heat is reflected by a surface, the line of reflection lies in the plane of incidence.

2. The angle of reflection is equal to the angle of incidence; that is, the reflected and incident rays make equal angles with the normal to the surface at the point of incidence.

We shall see hereafter that these laws are precisely the same as those of the reflection of light. In the case of light, they can be very strictly verified. And since, in all phenomena involving at once heat and light, we find the same laws holding for calorific as for luminous rays, we may consider the demonstration of these laws in the case of light as sufficient to prove that they hold good for rays of heat also.

310. Burning-mirrors.—The laws of the reflection of heat, however, may be directly verified by some well-known experiments, especially by means of a concave spherical mirror (Fig. 281), that is, a mirror consisting of a portion of a hollow sphere, with its concave side polished. The principal axis of this mirror is a line CF passing through the centre of the sphere, and through the middle point A (which may be called the *pole*) of the mirror itself. It may easily be deduced from the law of reflection that if a pencil of rays parallel to the axis are incident upon the mirror, they will all, after reflection, pass through or very near the point F which bisects the radius, and is called the principal focus. We may remark that the rays need not be parallel to the principal axis; it is only necessary that they be parallel to each other, in order that they should meet in a focus situated on the line drawn through the centre in a direction parallel to the pencil of rays.

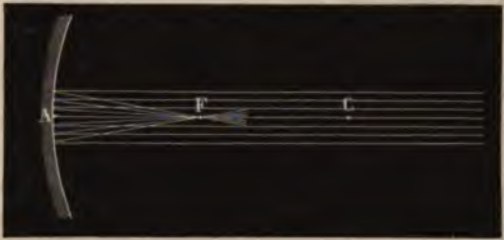


Fig. 281.—Focus of Concave Mirror.

These theoretical conclusions have been verified by experiments with burning-mirrors. These are spherical[1] concave mirrors, turning about an axis, so as to receive the rays of the sun perpendicularly upon their surface. The heat produced under these circumstances at the focus of the mirror, is sufficiently great to inflame any combustible material placed there, or even to produce more striking effects. Tschirnhausen's mirror, for instance, which was constructed in 1687, and was about 6½ feet in diameter, was able to melt copper or silver, and to vitrify brick. Instead of curved mirrors, Buffon employed a number of movable plane mirrors, which were arranged so that the different pencils of heat-rays reflected by them converged to nearly the same focus. In this way he obtained an extremely powerful effect, and was able, for instance, to set wood on fire at a distance of between 80 and 90 yards. This is the method which Archimedes is said to have employed for the destruction of the Roman fleet in the siege of Syracuse; and though the truth of the story is considered doubtful, it is not altogether absurd.

---

[1] *Parabolic* mirrors are perhaps more frequently employed for experiments on the reflection of heat. All rays falling on a parabolic mirror parallel to its axis are *accurately* reflected to its focus, and all rays incident upon it from a source of heat or light at the focus are reflected parallel to the axis.

The mirrors in the experiment of § 311 are most easily adjusted by first placing a source of light (such as the flame of a candle) in one focus, and forming a luminous image in the other. We have thus a convincing proof that heat and light obey the same laws as regards direction of reflection.

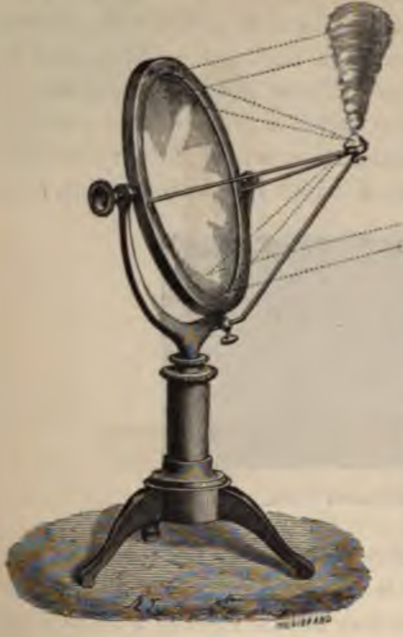


Fig. 282.—Burning Mirror.

311. Conjugate Mirrors.—A more rigorous demonstration of the laws of the reflection of heat is afforded by the celebrated experiment of the conjugate mirrors, which is generally ascribed to Pictet of Geneva.

Two spherical mirrors are placed at any convenient distance, with their concave surfaces towards each other and their axes in the same straight line. In the focus of one of them is placed a small furnace, or a red-hot cannon-ball, and in the focus of the other some highly inflammable material, such as phosphorus or gun-cotton. On exciting the furnace with bellows, the substance in the other focus immediately takes fire. With two mirrors of 14 inches diameter, gun-cotton may thus be set on fire at a distance of more than 30 feet. The explanation is very easy. The rays of heat coming from the focus of the first mirror are reflected in parallel lines, and, on impinging upon the surface of the second mirror, converge again to its focus, and are [illegible] concentrated upon the inflammable material placed there.

[illegible] appear at first sight that the experiment is not very pre- [illegible] the comparatively large size of the source of heat; but [illegible] that only a very small portion of this actually pro- [illegible] the rest serving merely to maintain a sufficiently [illegible] the points which really send rays to the focus.

Again, the image of the source of heat which is formed at the focus of the second mirror, is so small, that the slightest change in the position of either mirror causes the failure of the experiment. Great exactness is therefore required to insure success; and we may consequently regard the experiment as a tolerably severe test of the truth of the laws of reflection which have been quoted above.

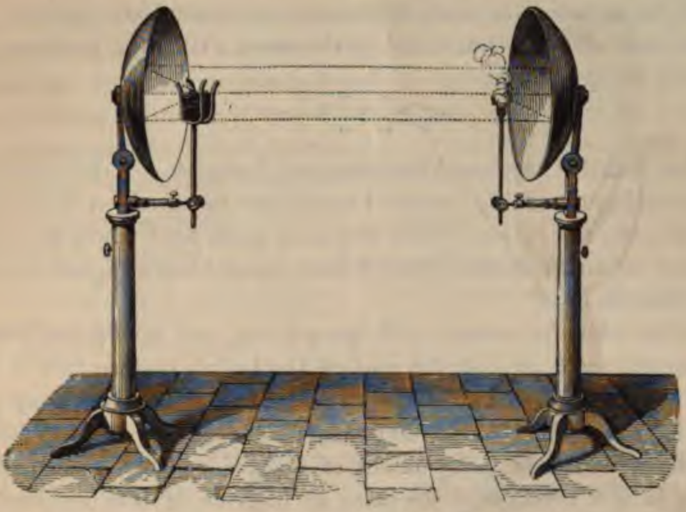


Fig. 283.—Conjugate Mirrors.

312. Different Properties of Bodies with respect to Radiant Heat.—Suppose a quantity of heat denoted by unity to be incident upon the surface of a body. This quantity will be divided into several distinct parts.

1. A portion will be regularly reflected according to the law given above. If the fraction of heat thus reflected be denoted by $\frac{1}{r}$, then $\frac{1}{r}$ is the measure of the *reflecting power.*

2. A portion $\frac{1}{d}$ will be irregularly reflected, and will be scattered or diffused through space in all directions. Thus $\frac{1}{d}$ is the measure of the *diffusive power.*

3. A portion $\frac{1}{a}$ will penetrate into the body so as to be absorbed by it, and to contribute to raise its temperature; $\frac{1}{a}$ is therefore the measure of the *absorbing power.*

4. Finally, we shall have, in many cases, a fourth portion $\frac{1}{\delta}$, which passes through the body without contributing to raise its temperature. This fraction, which exists only in the case of diathermanous bodies, is the measure of *diathermancy* or transmissive power.

The sum of these fractional parts must evidently make up the original unit; that is

$$\frac{1}{r}+\frac{1}{d}+\frac{1}{a}+\frac{1}{\delta}=1.$$

312 A. Relation between Absorption and Emission.—A different mode of expressing absorbing power is sometimes required—a mode which shall express the rate at which the body gains heat when completely inclosed in an exhausted space whose walls have a higher temperature than its own.

Let the walls be covered with lamp-black, and have a small excess of temperature θ, and let the area of the body's surface (which must have no concavities) be S; then the rate at which the body gains heat is proportional to $S\theta$, and may be denoted by $AS\theta$, A being a coefficient which is independent of θ provided that θ is small, but which is not necessarily the same at high as at low temperatures. We shall call this factor A the *coefficient of absorption;* and the heat gained by the body in a short interval of time τ will be

$$q=AS\theta\tau.$$

If now we suppose the inclosed body to be warmer than the walls by a small excess θ', the rate of losing heat will be proportional to $S\theta'$, and may be denoted by $ES\theta'$, E being called the coefficient of emission; and the quantity of heat lost by the body in the short time τ is

$$q'=ES\theta'\tau.$$

Now experiment shows that, for any given body at a given temperature, the values of A and E are equal; for example, a thermometer inclosed in a vacuous globe, as in the experiments of Dulong and Petit (§ 307 A), takes the same time to rise 1° as to fall 1° if the initial difference of temperature between the thermometer and the globe was 2° in each case.

The *coefficient of emission* then, at any given temperature, *is equal to the coefficient of absorption;* and we may therefore give it a symmetrical name, and call it the *coefficient of radiation.* A substance for which this coefficient has a large value is said to be a good radiator. Now it is obviously impossible for a body to absorb more heat than falls upon it. There must therefore be a limiting value of A applicable to a body whose absorbing power $\frac{1}{a}$ is unity; and the same limiting value must exist for E which is equal to A.

Hence it appears that good radiation depends rather upon defect of resistance than upon any positive power. A perfect radiator would be a substance whose surface opposed no resistance to the communication of radiant heat in either direction; while an imperfect radiator is one whose surface allows a portion to be communicated through it, and reflects another portion regularly or irregularly.

We may conveniently employ $\frac{1}{e}$ to denote the ratio of the heat emitted by a surface to that which would be emitted by a perfect radiator at the same temperature. We can then assert that for any one kind of heat

$$\frac{1}{e}=\frac{1}{a},$$

or the *emissive and absorptive powers are equal.*

The reflecting and diffusive powers of lamp-black are so insignificant, at temperatures below 100° C., that this substance is commonly adopted as the type of a perfect radiator, and the emissive and absorptive powers of other substances are usually expressed by comparison with it.

Recent experiments by Sir W. Thomson show that the coefficient of radiation A or E between two lamp-black surfaces radiating to each other in vacuo is about $\frac{1}{8000}$, q being expressed in gramme-degrees (§ 339), θ in degrees,[1] S in square centimetres of surface of the inclosed body, and τ in seconds.

312 B. Different Kinds of Heat-rays.—A beam of radiant heat or light is not, generally speaking, homogeneous, but (as we shall more fully explain in connection with optics) is made up of rays differing in wave-length, and capable of being separated by transmission through a prism, those which have the shortest wave-lengths being refracted or turned out of their original direction to the greatest extent. A beam of radiant heat or light may also possess peculiar properties comprehended under the name of polarization.

---

[1] It is immaterial whether the Cent. or Fahr. scale be employed—for the degree and gramme-degree change in the same ratio.

The experiments referred to (which will shortly be published in the Proc. Roy. Soc.), were conducted by observing the cooling of a copper ball in an inclosure filled with air. The total loss of heat corresponded to a co-efficient $\frac{1}{4000}$, and it was estimated that half the loss was due to atmospheric contact, and the other half to radiation.

Almost all substances exhibit the phenomenon of *selective absorption*, that is to say, they absorb some kinds of heat more readily than others; and it has been completely established by a variety of experiments, that the heat which a body emits when radiating to bodies colder than itself, consists chiefly of the same elementary heat-rays which it absorbs most copiously from bodies hotter than itself.

312 c. Theory of Exchanges.—Many of the phenomena of radiation are most simply explained by the view now usually called the *theory of exchanges*, but originally promulgated by Prévost of Geneva under the name of the theory of *mobile equilibrium of temperature*. This theory asserts that all bodies are constantly giving out radiant heat, at a rate depending upon their substance and temperature, but independent of the substance or temperature of the bodies which surround them;[1] and that, when a body is kept at a uniform temperature, it receives back just as much heat as it gives out.

According to this view, two bodies at the same temperature, exposed to mutual radiation, exchange equal amounts of heat; but if two bodies have unequal temperatures, that which is at the higher temperature gives to the other more than it receives in exchange.

As a necessary accompaniment of this view, it is maintained that, for each particular kind of heat, the emissive and absorbing powers $\frac{1}{e}$ and $\frac{1}{a}$ (§ 312 A) are equal for any one body, and at any given temperature; this inference being drawn from the well-known experimental fact that a body completely surrounded by an inclosure whose walls are preserved at a constant temperature, will ultimately take that temperature. For the details of the reasoning we must refer to special treatises.[2]

According to this theory, the coefficient A or E (§ 312 A) for a body at temperature $t°$, represents the difference between the absolute emission at this temperature and at the temperature $t° + 1°$.

313. Thermoscopic Apparatus employed in Researches connected with Radiant Heat.—An indispensable requisite for the successful study of radiant heat is an exceedingly delicate thermometer. For this purpose Leslie, about the beginning of the present century, invented the differential thermometer, with which he conducted some very important investigations, the main results of which are still acknowledged to be correct. Modern investigators, as Melloni,

---

[1] See § 307 A, formula (4) and foot-note.

[2] *Report on the Theory of Exchanges* by Balfour Stewart, in British Association Report, 1861, p. 97; and Stewart on *Heat*, book ii. chap. iii.

Laprovostaye, &c., have exclusively employed Nobili's thermo-multiplier, which is an instrument of much greater delicacy than the differential thermometer.

The thermo-pile inverted by Nobili, and improved by Melloni, consists essentially of a chain (Fig. 284) formed of alternate elements of bismuth and antimony. If the ends of the chain be connected by a wire, and the alternate joints slightly heated, a thermo-electric current will be produced, as will be explained hereafter. The amount of current increases with the number of elements, and with the difference of temperatures of the opposite junctions.

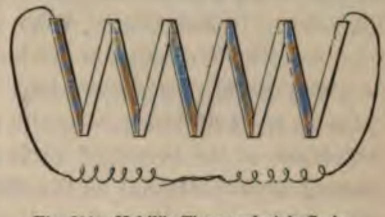


Fig. 284.—Nobili's Thermo-electric Series.

In the pile as improved by Melloni, the elements are arranged side by side so as to form a square bundle (Fig. 285), whose opposite ends consist of the alternate junctions. The whole is contained in a copper case, with covers at the two ends, which can be removed when it is desired to expose the faces of the pile to the action of heat.

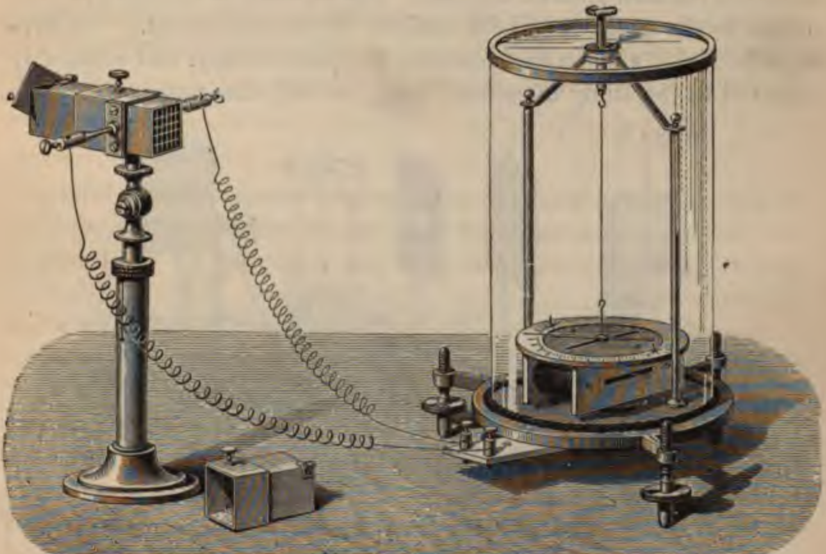


Fig. 285.—Melloni's Thermo-multiplier.

Two metallic rods connect the terminals of the thermo-electric series with wires leading to a galvanometer,[1] so that the existence of any current will immediately be indicated by the deflection of the needle. The amounts of current which correspond to different deflections are known from a table compiled by a method which we shall explain hereafter. Consequently, when a beam of radiant heat strikes the pile, an electric current is produced, and the amount of this current is given by the galvanometer. We shall see hereafter, when we come to treat of thermo-electric currents, that within certain limits, which are never exceeded in investigations upon radiant heat, the current is proportional to the difference of temperature between the two ends of the pile. Accordingly, as soon as all parts of the pile have acquired their permanent temperatures, the quantity of heat received during any interval of time from the source of heat will be equal to that lost to the air and surrounding objects. But this latter is, by Newton's law, proportional to the excess of temperature above the surrounding air, and therefore to the difference of temperature between the two ends of the pile. The current is therefore proportional to the quantity of heat received by the instrument. We have thus in Nobili's pile a thermometer of great delicacy, and admirably adapted to the study of radiant heat; in fact, the immense progress which has been made in this department of physics is mainly owing to this invention of Nobili.

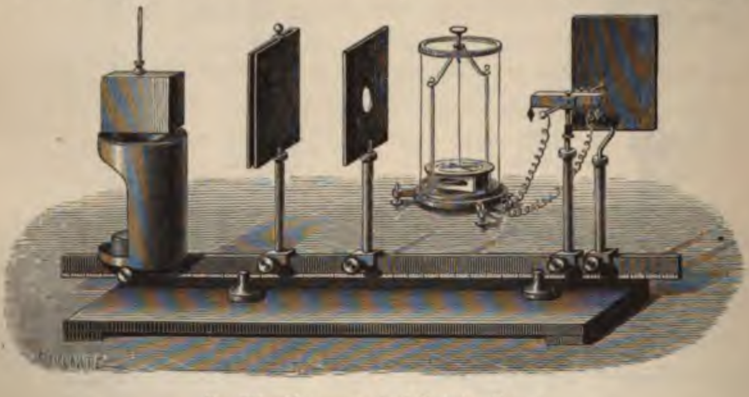


Fig. 286.—Measurement of Emissive Powers.

314. Measurement of Emissive Power.—The following arrangement was adopted by Melloni for the comparison of emissive powers. A graduated horizontal bar (Fig. 286) carries a cube, the different sides of which are covered with different substances. This is filled with water, which is maintained at the boiling-point by means of a spirit-lamp placed beneath. The pile is placed at a convenient distance, and the radiation can be intercepted at pleasure by screens arranged for the purpose. The whole forms what is called Melloni's apparatus.

---

[1] The pile and galvanometer together constitute the thermo-multiplier.

If we now subject the pile to the heat radiated from each of the faces in turn, we shall obtain currents proportional to the emissive powers of the substances with which the different faces are coated.

From a number of experiments of this kind it has been found that lamp-black has the greatest radiating power of all known substances, while the metals are the worst radiators. Some of the most important results are given in the following table, in which the emissive powers of the several substances are compared with that of lamp-black, which is denoted by 100:—

Relative Emissive Powers at 100° C.

Lamp-black,	100	Steel,	17
White-lead,	100	Platinum,	17
Paper,	98	Polished brass,	7
Glass,	90	Copper,	7
Indian ink,	85	Polished gold,	3
Shellac,	72	Polished silver,	3

316. Absorbing Power.—The method which most naturally suggests itself for comparing absorbing powers, is to apply coatings of different substances to that face of the pile which is exposed to the action of the source of heat. But this would involve great risk of injury to the pile.

The method employed by Melloni was as follows:—He placed in front of the pile a very thin copper disc (Fig. 287), coated with lamp-black on the side next the pile, and on the other side with the substance whose absorbing power was required. The disc absorbed heat by radiation from the source, of amount proportional to the absorbing power of this coating, and at the same time emitted heat from both sides in all directions. When its temperature became stationary, the amounts of heat absorbed and emitted were necessarily equal, and its two faces had sensibly equal temperatures.

Let E and E′ denote the coefficients of emission of lamp-black and of the substance with which the front was coated, and θ the excess of temperature of the disc above that of the air; then $(E+E')\theta$ is the heat emitted in unit time, if the area of each face is unity, and this must be equal to the heat absorbed in unit time.

But the indications of the thermo-pile are proportional to the heat radiated from the back alone, that is, to Eθ. The heat absorbed is therefore represented by the indication of the pile multiplied by $\frac{E+E'}{E}$.

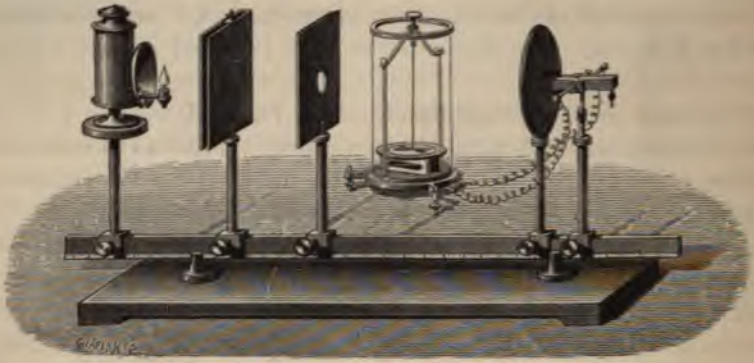


Fig. 287.—Measurement of Absorbing Powers.

In this way the absorbing powers given in the following list have been calculated from experiments of Melloni, the source of heat being a cube filled with water at 100° C.

RELATIVE ABSORBING POWERS AT 100° C.

Lamp-black,	100	Indian ink,	85
White-lead,	100	Shellac,	72
Isinglass,	91	Metal,	13

It will be observed that these numbers are identical with those which represent the emissive powers of the same substances.

317. Variation of Absorption with the Source.—The absorbing power varies according to the source of heat employed. In establishing this important fact, Melloni employed the following sources of heat:—

1. Locatelli's lamp, a small kind of oil-lamp, in which the level of [illegible] remains invariable, and which has a square-cut solid wick. [illegible] of heat it is of tolerably constant action, and it has been [illegible] in most of the experiments upon diathermancy. It is [illegible] Fig. 287.

2. Incandescent platinum. This is a spiral of platinum wire (Fig. 288) suspended over a spirit-lamp so as to envelop the flame. The metal is heated to a bright white heat; and since the radiating powers of the flame are very feeble, the metal may be regarded as the sole source of radiation. The flame, in fact, is scarcely distinguishable.

3. Copper heated to about 400° C. This is effected by placing a spirit-lamp behind a curved copper plate (Fig. 289).

4. Copper covered with lamp-black at 100° C. This is a cube containing boiling water (Fig. 290) similar to that already described in connection with the measurement of emissive powers. The face whose radiation is employed is covered with lamp-black.

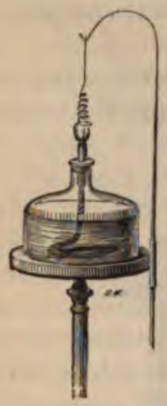


Fig. 288.
Incandescent Platinum.

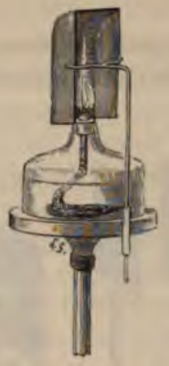


Fig. 289.
Copper heated to 400°.

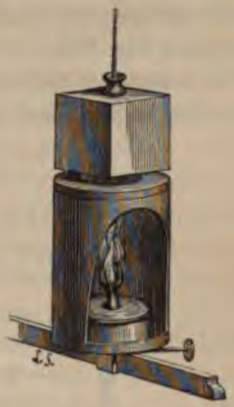


Fig. 290.
Cube at 100°.

If these different sources of heat be severally used in measuring absorbing powers, it will be found that these powers vary considerably according to the particular source of heat employed, and that if we denote the absorption of lamp-black in each case by 100, the relative absorbing powers of other substances are in general greater as the temperature of the source is lower. In establishing this important principle by experiment, the sources of heat are first placed at such distances that the direct radiation upon the pile shall be the same for each, and the pile is then replaced by the disc. The following table contains some of the results obtained by Melloni:—

Substances.	Locatelli's Lamp.	Incandescent Platinum.	Heated Copper.	Hot-water Cube.
Lamp-black, . . .	100	100	100	100
Indian ink, . . .	96	95	87	85
White-lead, . . .	53	56	89	100
Isinglass, ...	52	54	64	91
Shellac, ...	48	47	70	72
Metallic surface, .	14	13·5	13	13

319. Reflecting Power.—The reflecting power of a surface is measured by the proportion of incident heat which is regularly reflected from it. This subject has been investigated by Melloni, and by Laprovostaye and Desains. The arrangement used for the purpose is shown in Fig. 291.

The substance under investigation is placed upon the circular plate D, which is graduated round the circumference. The pile E is carried by the horizontal bar H H′, which turns about the pillar supporting the plate D. This bar is to be so adjusted as to make the reflected rays impinge upon the pile, the adjustment being made by the help of the divisions marked on the circular plate.

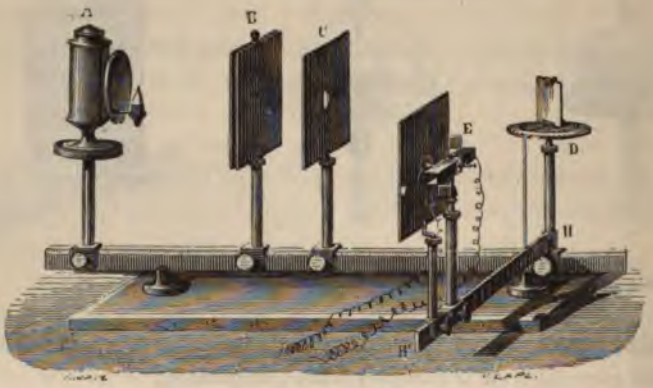


Fig. 291.—Measurement of Reflecting Power.

In making an observation, the bar H H′ is first placed so as to coincide with the prolongation of the principal bar, and the intensity of direct radiation is thus observed. The pile is then placed so as to receive the reflected rays, and the ratio of the intensity thus obtained to the intensity of direct radiation is the measure of the reflecting power.

The following are some of the results obtained by Laprovostaye and Desains, the source of heat employed being a Locatelli lamp:—

	Reflecting Power.		Reflecting Power.
Silver plate,	·97	Polished platinum,	·80
Gold,	·95	Steel,	·83
Brass,	·93	Zinc,	·81
Speculum metal,	·86	Iron,	·77
Tin,	·85		

Laprovostaye and Desains have also shown that, in the case of diathermanous substances, the reflecting power varies considerably with the angle of incidence, which is also the case for luminous rays.

In the case of metals, the change in the reflecting power produced by a change in the angle of incidence is not nearly so great; the reflecting power remains almost constant till about 70° or 80°, and when the angle of incidence exceeds this limit, the reflecting power decreases, whereas the opposite is the case with transparent bodies.

Finally, Laprovostaye and Desains have shown that, contrary to what was previously supposed, the reflecting power varies according to the source of heat. Thus the reflecting power of polished silver, which is ·97 for rays from a Locatelli lamp, is only ·92 for solar rays. In either case it will be seen that the reflecting powers of polished silver are very great; and since experiment has shown that luminous and calorific rays from the same source are reflected in nearly equal proportions, the advantages attending the use of silvered specula in telescopes can easily be understood.

320. Diffusive Power.—Diffusion is the irregular reflection of heat, doubtless owing to the minute inequalities of surface which are met with on even the most finely-polished bodies. The existence of this power may very easily be verified. We have only to let a beam of radiant heat fall upon any dead surface, for example on carbonate of lead. On placing the pile before the surface in any position, a deviation of the galvanometer is observed, which cannot be attributed to radiation from the surface, since in that case the effect, instead of instantly attaining its maximum, as it actually does, would increase gradually as the substance became warmed by the heat falling upon it.

Moreover the heat thus diffused, when the source of heat is a body at high temperature, such as a lamp-flame, is found to agree in its properties with the heat radiated from a body at high temperature, and to be altogether different from that which the diffusing surface is capable of radiating at its actual temperature. The diffused heat, for example, passes through a plate of alum without undergoing much absorption.

The diffusive power of powders, especially if white, is very considerable, as is shown by the following table taken from the results published by Laprovostaye and Desains:—

DIFFUSIVE POWER.	
White-lead,	·82
Powdered silver,	·76
Chromate of lead,	·66

The knowledge of this property enables us to explain the intense heat which is felt in the neighbourhood of a white wall lighted up by the sun.

Diffusion takes place in different proportions according to the direction, and is a maximum for points near the direction of the regularly-reflected ray.

The intensity of the diffused rays varies very considerably according to the source of heat employed. This was shown by Melloni in the following manner:—

He directed a ray of heat upon the surface of a disc of very thin card covered with a substance capable of diffusing the rays. The back of the disc was coated with lamp-black. When the different parts had acquired their permanent temperatures, the pile was placed in corresponding positions first before, and then behind the disc, so as to receive the heat due to both radiation and diffusion from the disc in the first case, and that due to radiation only in the second. It was found that the ratio of the two indications of the pile in these two positions varied very much according to the source of heat, the general rule being that the ratio of the diffused to the radiated heat was greatest when the source of heat was luminous, and at a high temperature.

321. Peculiar Property of Lamp-black.—If a similar experiment be performed with a card covered on both sides with lamp-black, it will be found that the difference between the indications of the pile in the two positions is very small. This difference, such as it is, may be accounted for by a slight difference of temperature between the two faces of the disc. We may therefore conclude that the whole of the heat has been absorbed by the lamp-black. This important result has been confirmed by direct experiments, which have failed to discover any trace of reflecting or diffusive power in this substance. Further, in the above experiment, the ratio of the indications in the two positions of the pile remains constant for all sources of heat; whence we see that the absorption of rays of heat by lamp-black is in all cases independent of the nature of the source. We thus see the advantage of applying a coating of lamp-black to all thermoscopic apparatus intended for the absorption of radiant heat.

322. Diathermancy.—It has long been known that some of the heat from an intensely luminous body, like the sun, could pass through certain transparent substances, such as glass; but it was, till recently, supposed that this could not happen in the case of dark, or even feebly luminous rays.

Pictet, of Geneva, was the first to establish the fact of diathermancy for radiant heat in general. He showed that a thermometer rose in temperature when exposed to radiation from a source of heat, notwithstanding the interposition of a transparent lamina; and the idea that this could be owing to the absorption and subsequent radiation of heat from the lamina was completely exploded by Prévost, who showed that the effect occurred even when the interposed substance was a sheet of ice. It is to Melloni, however, that we are indebted for the principal results which have been obtained in connection with this subject.

323. Influence of the Nature of the Substance.—The arrangement adopted by Melloni for testing the diathermancy of a solid body is that shown in Fig. 292. The Locatelli lamp A radiates its heat upon the pile E when the screen B is lowered; the hole in the screen C is for the purpose of limiting the pencil of rays. Direct radiation is first allowed to take place, and the resulting current as indicated by

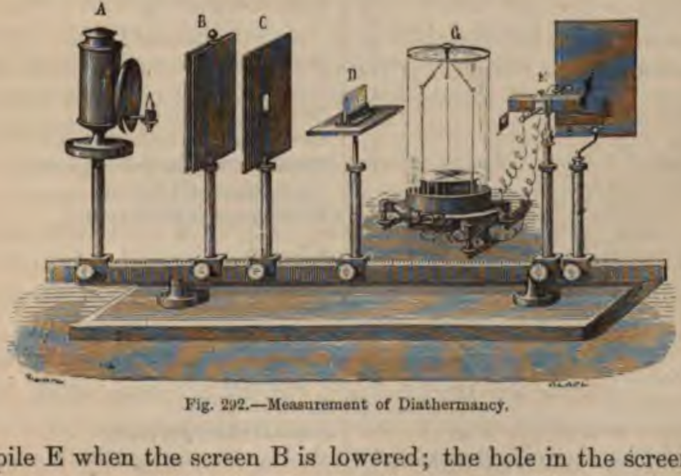


Fig. 292.—Measurement of Diathermancy.

the galvanometer G is noted. The diathermanous plate D is then interposed between the lamp and the pile, and the current is again measured; the ratio of the latter current to the former is the expression of the diathermancy of the plate.

In the case of liquids, Melloni employed narrow troughs with sides of very thin glass; the rays were first transmitted through the empty vessel, and then through the same vessel filled with liquid; the difference of the two results thus obtained being the measure of the heat stopped by the liquid. Specimens of the results are given in the following table:—

HEAT TRANSMITTED BY DIFFERENT SUBSTANCES FROM AN ARGAND LAMP.

(The direct heat is represented by 100.)

SOLIDS.

Colourless Glass.

(Thickness 1·85 mm.)

Flint-glass,	from 67 to 64
Plate-glass,	62 to 59
Crown-glass (French),	58
Crown-glass (English),	49
Window-glass,	54 to 50

Coloured Glass.

(Thickness 1·85 mm.)

Deep violet,	53
Pale violet,	45
Very deep blue,	19
Deep blue,	33
Light blue,	42
Mineral green,	23
Apple green,	26
Deep yellow,	40
Orange,	44
Yellowish red,	53
Crimson,	51

LIQUIDS.

(Thickness 9·21 mm.—A plate of glass of the same thickness gives 53.)

Colourless Liquids

Distilled water,	11
Absolute alcohol,	15
Sulphuric ether,	21
Sulphide of carbon,	63
Spirits of turpentine,	31
Pure sulphuric acid,	17
Pure nitric acid,	15
Solution of sea-salt,	12
Solution of alum,	12
Solution of sugar,	12
Solution of potash,	13
Solution of ammonia,	15

Coloured Liquids.

Nut-oil (yellow),	31
Colza-oil (yellow),	30
Olive-oil (greenish yellow),	30
Oil of carnations (yellowish)	26
Chloride of sulphur (reddish brown),	63
Pyroligneous acid (brown),	12
White of egg (slightly yellow),	11

CRYSTALLIZED BODIES.

(Thickness 3·62 mm.—A plate of glass of the same thickness gives 62.)

Colourless.

Rock-salt,	92
Iceland-spar,	12
Rock-crystal,	57
Brazilian topaz,	54
Carbonate of lead,	52
Borate of soda,	28
Sulphate of lime,	20
Citric acid,	15
Rock alum,	12

Coloured.

Smoky quartz (brown),	57
Aqua-marina (light blue),	29
Yellow agate,	29
Green tourmaline,	27
Sulphate of copper (blue),	0

It will be seen from this table that though diathermancy and transparency for light usually go together, the one is far from being a measure of the other. We see, for instance, that colourless nitric acid is much less diathermanous than strongly-coloured chloride of sulphur; and perfectly colourless alum allows much less heat to pass than deeply-coloured glass of the same thickness. Tyndall has shown that a solution of iodine in sulphide of carbon, though excessively opaque to light, allows heat to pass in large quantity.

The substance possessing the greatest diathermanous power is rock-salt, which allows the passage of ·92 of the incident heat. Common sea-salt only allows ·12 to pass. No such difference, however, attaches to solutions of these substances.

The diathermancy of gases has been investigated by Tyndall. The gases were contained in a long metallic tube with rock-salt ends; and, in order to obtain greater sensitiveness, a compensating cube filled with hot water was employed. This cube was placed at such a distance from one end of the thermo-pile as exactly to counterbalance the effect of the radiation from the principal source of heat when the tube was vacuous, so that the needle of the galvanometer in these circumstances stood at zero. The tube was then filled with different gases in turn, the compensating cube remaining unmoved; and the indications of the galvanometer were found to vary according to the gas employed. Compound gases stopped more than simple ones; the vapours of aromatic substances increased the absorptive power of dry air from 30 to 300 fold, and a similar effect was produced by the vapour of water, air more or less charged with aqueous vapour being found to exercise from 30 to 70 times the absorption of pure dry air.

It is probable that the aqueous vapour which is always present in the atmosphere greatly mitigates the heat of the solar rays, and also greatly retards the cooling of the earth by radiation at night. On the other hand, vapour being a better absorber is also a better radiator than dry air, a circumstance which conduces to the cooling and condensation of the upper portions of masses of vapour in the atmosphere, and the consequent formation of cloud.

324. Influence of Thickness.—From the experiments of Jamin and Masson, it appears that, when heat of definite refrangibility passes through a plate, the amount transmitted decreases in geometrical pr[illegible] as the thickness increases in arithmetical progression; a re[illegible] may also be expressed by saying, that if a plate be divided in imagination into laminæ of equal thickness, the ratio of the heat absorbed to the heat transmitted is the same for them all.

In the case of mixed radiation, such as is emitted by nearly all available sources of heat, we must suppose this law to hold for each separate constituent; but some of these are more easily absorbed than others, and as these accordingly diminish in amount more rapidly than the others, the beam as it proceeds on its way through the plate acquires a character which fits it for transmission rather than absorption. Hence the foremost layers absorb much more than the later ones, if the plate be of considerable thickness.

In the case of bodies which are opaque to heat, absorption and radiation are mere surface-actions. But in diathermanous substances, as we have seen, absorption goes on in the interior, so that a thick plate absorbs more heat than a thin one. The same thing is true as regards radiation:—a diathermanous substance radiates from its interior as well as from its surface, as proved by the fact that a thick plate radiates more heat than a thin one at the same temperature.

325. Relation between Radiant Heat and Light.—The property in virtue of which particular substances select particular kinds of heat for absorption and other kinds for transmission, was called by Melloni *thermochrose* (literally heat-colour), from its obvious analogy to what we call colour in the case of light. A piece of coloured glass, for example, selects rays of certain colours (or vibration-periods) for absorption, and transmits the rest, what we call the colour of the glass being determined by those which it transmits.

It is now believed that thermochrose and colour are not merely analogous but essentially identical. Prismatic analysis shows that rays exist of refrangibilities much greater and much less than those which compose the luminous spectrum. The spectrum of the electric light, for example, extends on both sides of the visible spectrum to distances considerably exceeding the length of the visible spectrum itself. The invisible ultra-violet rays can be detected by their chemical action, or by causing them to fall upon certain substances (called *fluorescent*) which become luminous when exposed to their action, but have exceedingly small heating effect. The heat becomes considerable in the yellow portion of the spectrum, stronger in the red, and goes on increasing in the invisible portion beyond the red, up to a certain point, beyond which it gradually diminishes till it becomes inappreciable.

It would, however, be an error to suppose that there is a heat spectrum consisting of distinct rays from those which form the luminous spectrum, and that the two spectra are superimposed one upon the other. There is every reason for believing that the contrary is the fact, and that the radiations which constitute heat and light are essentially identical. In operating upon rays of definite refrangibility, it is never found possible to diminish their heating and illuminating powers in unequal proportions; an interposed plate of any partially transparent material, if it stops half the light, also stops half the heat.

It is true that the most intense heat is not found in the most luminous portion of the spectrum; but it is probable that the eye, like the ear, is more powerfully affected by quick than by slow vibrations when the amount of energy is the same; and as a treble note contains far less energy than a bass note which strikes the ear as equally loud, so a blue ray contains much less energy than a red ray if they strike the eye as equally bright.

The invisibility—at least to human eyes—of the ultra-red and ultra-violet rays may be due either to the absorption of these rays by the humours of the eye before they can reach the retina, or to the inability of our visual organs to take up vibrations quicker than the violet or slower than the red.

A body at a low temperature (say 100° C.) emits only dark heat. As the temperature rises, the emission of dark heat becomes more energetic, and at the same time rays of a more refrangible character are added. This strengthening of the rays formerly emitted, with the continual addition of new rays of higher refrangibility, goes on as long as the temperature of the body continues to rise. The luminosity of the body begins with the emission of the least refrangible of the visible rays, namely the red, and goes on to include rays of other colours as it passes from a red to a white heat. Tyndall, by thus gradually raising the temperature of a platinum spiral, obtained the following measures of the heat received in a definite position in the dark portion of the spectrum:—

Appearance of Spiral.	Heat Received.
Dark,	1
Dark,	6
Faint red,	10
Dull red,	13
Red,	18
Full red,	27
Orange,	60
Yellow,	93
Full white,	122

Generally speaking, the rays which fall within the limits of the visible spectrum are the most transmissible, and the extreme rays at both ends of the complete spectrum are the soonest absorbed. This is probably the reason why the invisible portion of the solar spectrum, though extending to a considerable distance in both directions, is less extensive than that of the electric light. The extreme rays have probably been absorbed by the earth's atmosphere.

Ordinary glass is comparatively opaque to both classes of dark rays. Rock-salt surpasses all other substances in its transparency to the dark rays beyond the red; and quartz (rock-crystal) is very transparent to the dark rays beyond the violet. Alum is remarkable as a substance which is exceedingly opaque to the ultra-red rays, though exceedingly transparent to visible rays; and Tyndall has found that a solution of iodine in sulphide of carbon is, on the contrary, highly transparent to the ultra-red and opaque to the luminous rays.

Great interest was excited some years ago by Stokes' discovery that the ultra-violet rays, when they fall upon fluorescent substances, undergo a lowering of refrangibility which brings them within the limits of human vision. Akin subsequently proposed the inquiry whether it was possible, by a converse change, to transform the ultra-red into visible rays, and Tyndall, by taking advantage of this peculiar property of the solution of iodine, succeeded in effecting the transformation. He brought the rays of the electric lamp to a focus by means of a reflector, and, after stopping all the luminous rays by interposing a vessel with rock-salt sides, containing the solution of iodine, he found that a piece of platinum foil, when brought into the focus, was heated to incandescence, and thus emitted light as well as heat. To this transformation of dark radiant heat into light he gave the name of *calorescence.*

326. Selective Emission and Absorption.—In order to connect together the various phenomena which may be classed under the general title of selective radiation and absorption, it is necessary to form some such hypothesis as the following. The atoms or molecules of which any particular substance is composed, must be supposed to be capable of vibrating freely in certain periods, which, in the case of gases, are sharply defined, so that a gas is like a musical string, which will vibrate in unison with certain definite notes and with no intermediate ones. The particles of a solid or liquid, on the other hand, are capable of executing vibrations of any period lying between certain limits; so that they may perhaps be compared to the body of a violin, or to the sounding-board of a piano; and these limits (or at all events the upper limit) alter with the temperature, so as to include shorter periods of vibration as the temperature rises.

These vibrations of the particles of a body are capable of being excited by vibrations of like period in the external ether, in which case the body absorbs radiant heat. But they may also be excited by the internal heat of the body; for whenever the molecules experience violent shocks, which excite tremors in them, these are the vibrations which they tend to assume. In this case the particles of the body excite vibrations of like period in the surrounding ether, and the body is said to emit radiant heat.

One consequence of these principles is that a diathermanous body is particularly opaque to its own radiation. Rock-salt transmits 92 per cent. of the radiation from most sources of heat; but if the source of heat be another piece of rock-salt, especially if it be a thin plate, the amount transmitted is much less, a considerable proportion being absorbed. The heat emitted and absorbed by rock-salt is of exceedingly low refrangibility.

Glass largely absorbs heat of long period, such as is emitted by bodies whose temperatures are not sufficiently high to render them luminous, but allows rays of shorter period, such as compose the luminous portion of the radiation from a lamp-flame, to pass almost entire. Accordingly glass when heated emits a copious radiation of non-luminous heat, but comparatively little light.

Experiment shows that if various bodies, whether opaque or transparent, colourless or coloured, are heated to incandescence in the interior of a furnace, or of an ordinary coal-fire, they will all, while in the furnace, exhibit the same tint, namely the tint of the glowing coals. In the case of coloured transparent bodies, this implies that the rays which their colour prevents them from transmitting from the coals behind them are radiated by the bodies themselves most copiously; for example, a glass coloured red by oxide of copper permits only red rays to pass through it, absorbing all the rest, but it does not show its colour in the furnace, because its own heat causes it to radiate just those rays which it has the power of absorbing, so that the total radiation which it sends to the eye of a spectator, consisting partly of the radiation due to its own heat, and partly of rays which it transmits from the glowing fuel behind it, is exactly the same in kind and amount as that which comes direct from the other parts of the fire. This explanation is verified by the fact that such

CHAPTER XXX.

CONDUCTION OF HEAT.

328. Conduction.—When heat is applied to one end of a bar of metal, it is propagated through the substance of the bar, producing a rise of temperature, which is first perceptible at near and afterwards at remote portions. This transmission of heat is called *conduction*, and it differs notably from radiation (1), in being gradual instead of instantaneous; and (2), in exhibiting no preference for rectilinear transmission, the propagation of heat being as rapid through a crooked as through a straight bar.

328 A. Definition of Conductivity or Specific Conducting Power.—If the application of heat to one end of the bar be continued for a sufficiently long time, and with great steadiness, the different portions of the bar will at length cease to rise in temperature, and will retain steadily the temperatures which they have acquired. We may thus distinguish two stages in the experiment: 1st, the variable stage, during which all portions of the bar are rising in temperature; and, 2d, the permanent state, which may subsist for any length of time without alteration. In the former stage the bar is gaining heat; that is, it is receiving more heat from the source than it gives out to surrounding bodies. In the latter stage the receipts and expenditure of heat are equal, and are equal not only for the bar as a whole, but for every small portion of which it is composed.

In the permanent state no further accumulation of heat takes place. All the heat which reaches an internal particle is transmitted by conduction, and the heat which reaches a superficial particle is given off partly by radiation and air-contact, and partly by conduction to colder neighbouring particles. In the earlier stage, on the contrary, only a portion of the heat received by a particle is thus disposed of, the remainder being accumulated in the particle, and serving to raise its temperature.

In order to obtain results depending on conduction free from complications arising from differences of specific heat (§ 340), we must, in all cases, wait for the permanent state. In the earlier stage great specific heat acts as an obstacle to rapid transmission, and a body of great specific heat would be liable to be mistaken for a body of small conductivity.

The measurement of the conductivity of a substance is still further simplified by making the flow of heat through it take place entirely in one definite direction (that is to say in parallel lines), avoiding all cross-currents. To this end it is necessary that all points in the same cross section should have the same temperature, a condition which is not strictly fulfilled in the bar above described, as the surface will be cooler than the interior. It is nearly fulfilled in the axial portions of the bar, and it is very nearly fulfilled in the central portions of a uniform plate whose breadth in all directions is a very large multiple of its thickness, when the whole of one face is maintained as nearly as practicable at one uniform temperature, and the other face at another uniform temperature. In the central portions of such a plate, the flow of heat will be perpendicularly through the plate; and when the permanent state has arrived, the amount of heat that passes in a unit of time through a cross section of area A, will be expressed by the formula

$$Q = k\,A\,\frac{t_2 - t_1}{x}, \qquad (1)$$

where x is the thickness of the plate, t_1 and t_2 the temperatures of its two faces, and k a coefficient depending on the material of the plate. This coefficient k is the *conductivity* of the material. It may be defined as *the quantity of heat which flows in unit time through a cross section of unit area, when the thickness of the plate is unity, and one face is warmer by 1° than the other.*[1]

---

[1] The method of taking account of conductivity during the variable stage may be illustrated by considering the simplest case,—that in which the flow of heat is in parallel lines.

Let x denote distance measured in the direction in which heat is flowing, v the temperature at the time t at a point specified by x, k the conductivity, and c the thermal capacity per unit volume (both at the temperature v). Then the flow of heat per unit time past a cross section of area A is $-k\,A\frac{dv}{dx}$, and the flow past an equal and parallel section further on by the small distance δx is greater by the amount

$$A\frac{d}{dx}\left(-k\frac{dv}{dx}\right)\delta x.$$

This [illegible]n therefore represents the loss of heat from the intervening prism $A\,\delta x$, Forbes' experiments have shown that the conductivity of a substance is not the same at all temperatures. In view of this fact, k in the above formula denotes the average conductivity between the temperatures t_1 and t_2. The variation of conductivity with temperature is, however, comparatively small.

329. Differences of Conductivity.—The following experiments are often adduced in illustration of the different conducting powers of different solids.

Two bars of the same size but of different materials (Fig. 293) are placed end to end, and small wooden balls are attached by wax to their under-surfaces at equal distances. The bars are then heated at their contiguous ends, and, as the heat extends along them, the wax melts, and the balls successively drop off. If the heating is continued till the permanent state arrives, it may generally be concluded that the bar which has lost most balls is the best conductor, especially if both bars have been coated with the same varnish, so as to make their radiating powers equal.

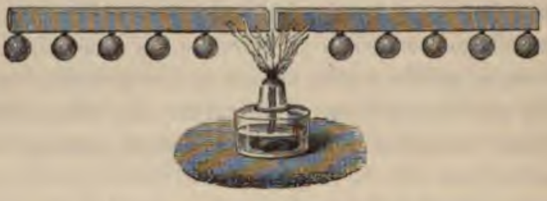


Fig. 293.—Balls Melted off.

The well-known experiment of Ingenhousz is of the same kind. The apparatus consists of a copper box having a row of holes in one of its faces, in which rods of different materials can be fixed. The

---

and the resulting fall of temperature is the quotient of the loss by the thermal capacity $cA\,\delta x$, which quotient is

$$\frac{1}{c}\frac{d}{dx}\left(-k\frac{dv}{dx}\right).$$

This, then, is the fall of temperature per unit time, or is $-\frac{dv}{dt}$. If the range of temperature is small enough to admit of our regarding k and c as constant, the equation becomes

$$\frac{dv}{dt}=\frac{k}{c}\frac{d^2v}{dx^2},$$

which applies approximately to the variations of temperature in the soil near the surface of the earth, x being in this case measured vertically. For the integral of this equation, see *Trans. Roy. Soc. Edin.* vol. xxii. part ii. p. 438.

rods having previously been coated with wax, the box is filled with boiling water, which comes into contact with the inner ends of the rods. The wax gradually melts as the heat travels along the rods; and, if the experiment is continued till the melting reaches its limit, those rods on which it has extended furthest are, generally speaking, the best conductors.

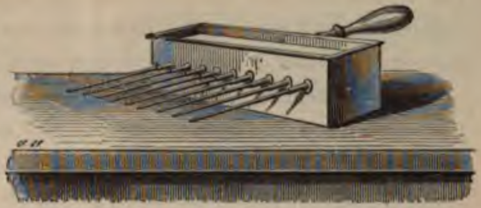


Fig. 294.—Ingenhousz's Apparatus.

It is thus found that metals are unequally good conductors of heat, and that they may be arranged in the following order, beginning with the best conductors:—*Silver, copper, gold, brass, tin, iron, lead, platinum, bismuth.*

In both these experiments we must beware of attempting to measure conductivity by the *quickness* with which the melting advances. This quickness may be simply an indication of small specific heat.[1]

330. Conducting Power of Metals.—Metals, though differing considerably one from another, are as a class greatly superior in conductivity to other substances, such as wood, marble, brick. This explains several familiar phenomena. If the hand be placed upon a metal plate at the temperature of 10° C., or plunged into mercury at this temperature, a very marked sensation of cold is experienced. This sensation is less intense with a plate of marble at the same temperature, and still less with a piece of wood. The reason is that the hand, which is at a higher temperature than the substance to which it is applied, gives up a portion of its heat, which is conducted away by the substance, and consequently a larger portion of heat is parted with, and a more marked sensation of cold experienced, in the case of the body of greater conducting power.

331. Davy Lamp.—The conducting power of metals explains the curious property possessed by wire-gauze of cutting off a flame. If, for example, a piece of wire-gauze be placed above a jet of gas, the flame is prevented from rising above the gauze. If the gas be first allowed to pass through the gauze, and then lighted above, the flame is cut off from the burner, and is unable to extend itself to the under-surface of the gauze. These facts depend upon the conducting power of metallic gauze, in virtue of which the heat of the flame is rapidly dissipated at the points of contact, the result being a diminution of temperature sufficient to prevent ignition.

---

[1] Strictly speaking, *small specific heat per unit volume*, not, as usual, *per unit mass.*

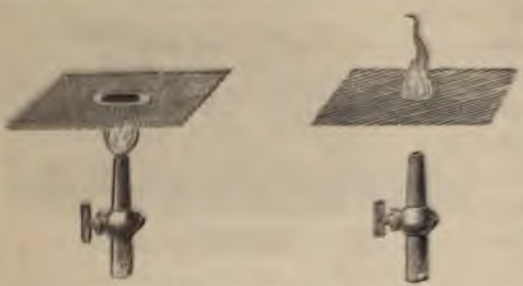


Fig. 295.—Action of Wire-gauze on Flame.

This property of metallic gauze has been turned to account for various purposes, but its most useful application is in the safety-lamp of Sir Humphrey Davy. It is well known that a gas called *fire-damp* is often given off in coal-mines. It is a compound of carbon and hydrogen, and is a large ingredient in ordinary coal-gas.

This fire-damp, when mixed with eight or ten times its volume of air, explodes with great violence on coming in contact with a lighted body. To obviate this danger, Davy invented the safety-lamp, which is an ordinary lamp with the flame inclosed by wire-gauze. The explosive gases pass through the gauze, and burn inside the lamp, in such a manner as to warn the miner of their presence; but the flame is unable to pass through the gauze.

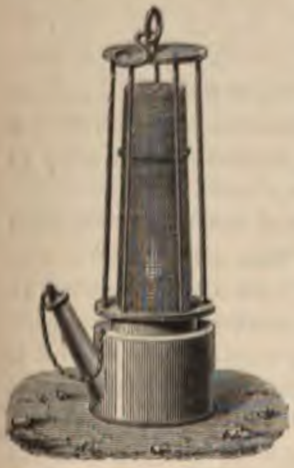


Fig. 296.—Davy Lamp.

332. Various Applications.—The knowledge of the relative conducting powers of different bodies has several important practical applications.

In cold countries, where the heat produced in the interior of a house should be as far as possible prevented from escaping, the walls should be of brick or wood, which have feeble conducting powers. If they are of stone, which is a better conductor, a greater thickness is required. Thick walls are also useful in hot countries in resisting the power of the solar rays during the heat of the day.

We have already alluded (§ 224) to the advantage of employing fire-brick, which is a bad conductor, as a lining for stoves.

The feeble conducting power of brick has led to its employment in the construction of ice-houses. These are round pits, generally from 6 to 8 yards in diameter at top, and somewhat narrower at the bottom, where there is a grating to allow the escape of water. The inside is lined with brick, and the top is covered with straw, which, as we shall shortly see, is a bad conductor. In order to diminish as much as possible the extent of surface exposed to the action of the air, the separate pieces are dipped in water before depositing them in the ice-house, and, by their subsequent freezing together, a solid mass is produced, capable of remaining unmelted for a very long time.

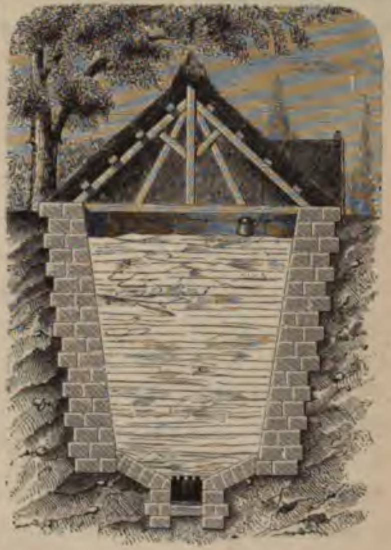


Fig. 297.—Ice-house.

333. Experimental Determination of Conductivity.—Several experimenters have investigated the conductivity of metals, by keeping one end of a metallic bar at a high temperature, and, after a sufficient lapse of time, observing the permanent temperatures assumed by different points in its length.

If the bar is so long that its further end is not sensibly warmer than the surrounding air, and if, moreover, Newton's law of cooling be assumed true for all parts of the surface, and all parts of a cross section be assumed to have the same temperature, the conductivity being also assumed to be independent of the temperature, it is easily shown that the temperatures of the bar at equidistant points in its length, beginning from the heated end, must exceed the atmospheric temperature by amounts forming a decreasing geometric series. Wiedemann and Franz, by the aid of the formula to which these assumptions lead,[1] computed the relative conducting powers of several of the metals, from experiments on thin bars, which were steadily heated at one end, the temperatures at various points in the length being determined by means of a thermo-electric junction clamped to the bar. The following were the results thus obtained:—

---

[1] If p and s denote the perimeter and section of the bar, k the conductivity, and h the coefficient of emission of the surface at the temperature v, the heat emitted in unit time from the length δx is $h v p \delta x$, if we assume as our zero of temperature the temperature of the surrounding air. But the heat which passes a section is $s k \frac{dv}{dx}$, and that

RELATIVE CONDUCTING POWERS.

Silver,	100	Steel,	12
Copper,	77·6	Iron,	11·9
Gold,	53·2	Lead,	8·5
Brass,	33	Platinum,	8·2
Zinc,	19·9	Palladium,	6·3
Tin,	14·5	Bismuth,	1·9

The *absolute* conductivity of wrought iron was investigated with great care by Professor J. D. Forbes, by a method which avoided some of the questionable assumptions above enumerated. The end of the bar was heated by a bath of melted lead kept at a uniform temperature, screens being interposed to protect the rest of the bar from the heat radiated by the bath. The temperatures at other points were observed by means of thermometers inserted in small holes drilled in the bar, and kept in metallic contact by fluid metal. In order to determine the loss of heat by radiation at different temperatures, a precisely similar bar, with a thermometer inserted in it, was raised to about the temperature of the bath, and the times of cooling down through different ranges were noted.

The conductivity of one of the two bars experimented on, varied from ·01337 at 0° C. to ·00801 at 275° C., and the corresponding numbers for the other bar were ·00992 and ·00724, the units being the foot, the minute, the degree (of any scale), and the foot-degree[1] (of the same scale). In both instances, the conductivity decreased regularly with increase of temperature.

Absolute determinations have also been made of the conductivity of the soil or rock at three localities in or near Edinburgh, by Pro-

which passes a section further on by the amount δx is less by the amount $sk \frac{d^2 v}{dx^2} \delta x$; and this difference must equal the amount emitted from the intervening portion of the surface. Hence we have the equation $\frac{d^2 v}{dx^2} = \frac{hp}{ks} v$, the integral of which for the case supposed is

$$v = \mathrm{V} e^{-x\sqrt{\frac{hp}{ks}}},$$

V denoting the temperature at the heated end.

[1] See §§ 339, 340.

fessor Forbes and Sir W. Thomson. When expressed in terms of the above units, they are—

Trap-rock of Calton Hill,	·000268
Sand of Experimental Garden,	·000169
Sandstone of Craigleith Quarry,	·000689

These determinations were derived from observations on the temperature of the soil as indicated by thermometers having their bulbs buried at depths of from 3 to 24 feet. The annual range of temperature diminished rapidly as the depth increased; and this diminution of range was accompanied by a retardation of the times of maximum and minimum. To deduce the conductivity,[1] it was necessary first to reduce the annual variation of each thermometer to the sum of a number of terms each of which would express a *simple harmonic variation* or *simple vibration* (§ 53 A), the most important of these being the annual term, which represents a simple vibration whose period is a year. By comparing the amplitudes of this term at two different depths, we obtain the value of $\frac{k}{c}$, k denoting conductivity, and c capacity per unit volume; and another independent determination of the same element is obtained by comparing the *epochs*, in other words by noting the *retardation of phase* which this term undergoes. The value of c was determined by direct experiments conducted by Regnault, and lastly, this value multiplied by $\frac{k}{c}$ gave the conductivity k.

334. Conducting Powers of Liquids.—With the exception of mercury and other melted metals, liquids are exceedingly bad conductors of heat. This can be shown by heating the upper part of a column of liquid, and observing the variations of temperature below. These will be found to be scarcely perceptible, and to be very slowly produced. If the heat were applied below (Fig. 298), we should have the process called *convection of heat;* the lower layers of liquid would rise to the surface, and be replaced by others which would rise in their turn, thus producing a circulation and a general heating of the liquid. On the other hand, when heat is applied above, the expanded layers remain in their place, and the rest of the liquid can be heated by conduction and radiation only.

---

[1] The process of reduction is fully explained, both theoretically and practically, in two (by Sir W. Thomson and the Editor of this work) in the *Trans. Roy. Soc. Edin.*

The following experiment is one instance of the very feeble conducting power of water. A piece of ice is placed at the bottom of a glass tube (Fig. 299), which is then partly filled with water; heat is applied to the middle of the tube, and the upper portion of the water is readily raised to ebullition, without melting the ice below.

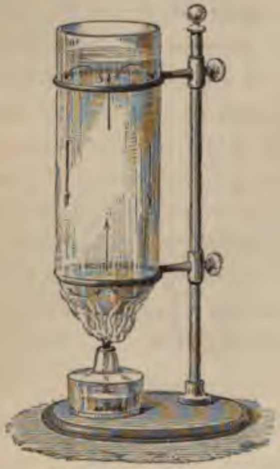


Fig. 298.—Liquid heated from below.

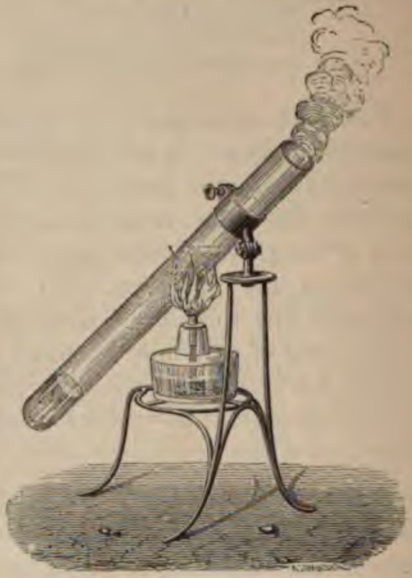


Fig. 299.—Boiling of Water over Ice.

335. Measure of the Conducting Power of Water.—The power of conducting heat possessed by water, though very small, is yet capable of measurement. This was established by Despretz by the following experiment. He took a cylinder of wood (Fig. 300) about a yard in height and eight inches in diameter, which was filled with water. In the side of this cylinder were arranged twelve thermometers one above another, their bulbs being all in the same vertical through the middle of the liquid column. On the top of the liquid rested a metal box, which was filled with water at 100°, frequently renewed during the course of the experiment. Under these circumstances Despretz observed that the temperature of the thermometers rose gradually, and that a long time—about 30 hours—was required before the permanent state was assumed. Their permanent differences, which formed a decreasing geometric series, were very small, and were inappreciable after the sixth thermometer.

The increase of temperature indicated by the thermometers might be attributed to the heat received from the sides of the cylinder, though the feeble conducting power of wood renders this idea somewhat improbable. But Despretz observed that the temperature was higher in the axis of the cylinder than near the sides, which proves that the elevation of temperature was due to the passage of heat downwards through the liquid.

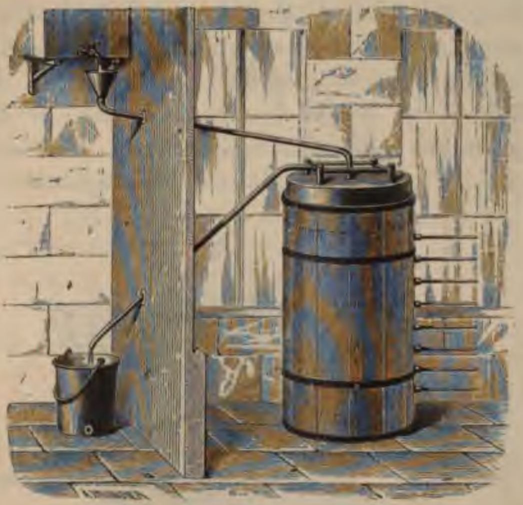


Fig. 300.—Despretz's Experiment.

From recent experiments by Professor Guthrie,[1] it appears that water conducts better than any other liquid except mercury.

336. Conducting Power of Gases.—Of the conducting powers of gases it is almost impossible to obtain any direct proofs, since it is exceedingly difficult to prevent the interference of convection and direct radiation. However, we know at least that they are exceedingly bad conductors. In fact, in all cases where gases are inclosed in small cavities where their movement is difficult, the system thus formed is a very bad conductor of heat. This is the cause of the feeble conducting powers of many kinds of cloth, of fur, eider-down, felt, straw, saw-dust, &c. Materials of this kind, when used as articles of clothing, are commonly said to be *warm*, because they hinder the heat of the body from escaping. If a garment of eider-down or fur were compressed so as to expel the greater part of the air, and to reduce the substance to a thin sheet, it would be found to be a much less warm covering than before, having become a better conductor. We thus see that it is the presence of air which gives these substances their feeble conducting power, and we are accordingly justified in assuming that air is a bad conductor of heat.

---

[1] *B. A. Report*, 1868, and [illegible] 1869.

337. Norwegian Stove.—A curious application of the bad conducting power of felt is occasionally to be seen in the north of Europe, in a kind of self-acting cooking-box. This is a box lined inside with a thick layer of felt, into which fits a metallic dish with a cover. The dish is then covered with a cushion of felt, so as to be completely surrounded by a substance of very feeble conducting power. The method of employing the apparatus is as follows:—The meat which it is desired to cook is placed along with some water in the dish, the whole is boiled for a short time, and then transferred from the fire to the box, where the cooking is completed *without any*

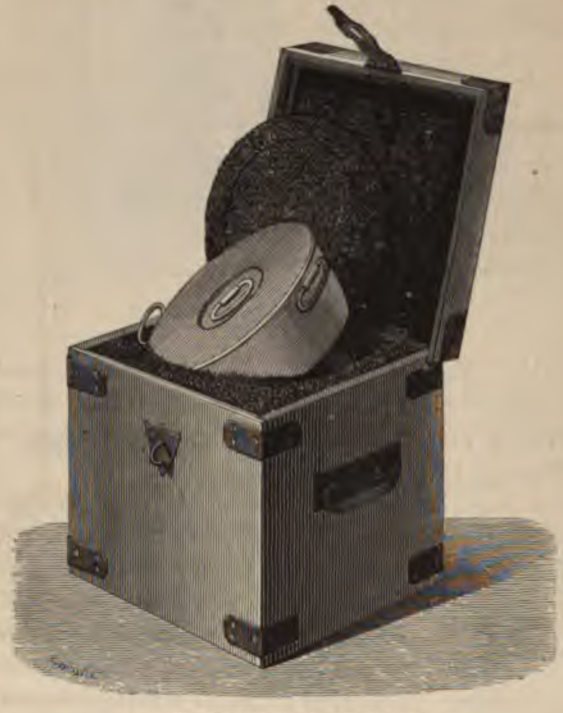


Fig. 301.—Norwegian Cooking-box.

farther application of heat. The isolating power of the stuffing of the box, as far as regards heat, is exceedingly great; in fact, it may be shown that at the end of three hours the temperature of the water has fallen by only about 10° or 15° C., and has accordingly remained during all that time sufficiently high to conduct the operation of cooking.

338. Conductivity of Hydrogen.—The conducting power of hydrogen is much superior to that of the other gases—a fact which agrees with the view entertained by chemists, that this gas is the vapour of a metal. The good conductivity of hydrogen is shown by the following experiments:—

1. Within a glass tube (Fig. 302) is stretched a thin platinum wire, which is raised to incandescence by the passage of an electric current. When air, or any gas other than hydrogen, is passed through the tube, the incandescence continues, though with less vividness than in vacuo; but it disappears as soon as hydrogen is employed.

2. A thermometer is placed at the bottom of a vertical tube, and heated by a vessel containing boiling water which is placed at the top of the tube. The tube is exhausted of air, and different gases are successively admitted. In each case the indication of the thermometer is found to be lower than for vacuum, except when the gas is hydrogen. With this gas, the difference is in the opposite direction, showing that the diminution of radiation has been more than compensated by the conducting power of the hydrogen.

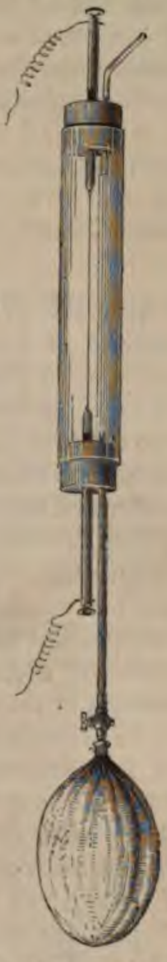


Fig. 302.—Cooling by Contact of Hydrogen.

CHAPTER XXXI.

CALORIMETRY.

339. Quantities of Heat.—Calorimetry consists in the measurement of quantities of heat. This can be effected without making any assumption as to what heat is. It merely presupposes the power of identifying equal quantities.

If two different thermic actions, of which one may be friction, and the other combustion, when separately applied to the heating of a pound of water, raise its temperature in each case from 0° C. to 1° C., we say that the water receives equal quantities of heat in both cases; and the quantity of heat required to raise m pounds of water from 0° C. to 1° C. would be m times as great.

In order to test whether the quantity of heat required to raise the temperature of a pound of water by 1° C. is the same at all initial temperatures of the water, we may employ the method of mixtures. Let us, for example, mix 3 lbs. of water at 15° with 5 lbs. at 35°, and observe the temperature of the mixture. If this temperature be denoted by x, the 3 lbs. have risen through the range $x-15$, and the 5 lbs. have fallen through the range $35-x$. If a rise or fall of 1° involves the same gain or loss of heat at all temperatures, the quantity of heat gained by the 3 lbs. may be represented by $3\ (x-15)$, and the heat lost by the 5 lbs. will be represented by $5\ (35-x)$. But what the one has gained the other has lost; we have therefore

$$3\ (x-15)=5\ (35-x),$$

whence

$$x=27{\cdot}5.$$

Calculation, based on this principle, is found to agree very accurately with experiment up to about 40° C. We may therefore define the *unit of heat* as the *quantity of heat required to raise the temperature of unit mass of water* 1°, between the limits 0° C. and 40° C.

Several different units of heat are employed, all having reference to pure water between these limits of temperature.

The gramme-degree (Centigrade) is the quantity of heat required to raise a gramme of water 1° (Centigrade).

The kilogramme-degree (Centigrade) is the heat required to raise a kilogramme of water 1° (Centigrade). It is sometimes called the *calorie.*

The pound-degree (Fahrenheit or Centigrade) is the heat required to raise a pound avoirdupois of water 1°.

The foot-degree (Fahrenheit or Centigrade) is the heat required to raise a cubic foot of water 1°.

We shall briefly describe in this chapter three of the most important applications of calorimetry:—

1. In connection with changes of temperature (specific heat);
2. In connection with change of state (latent heat);
3. In connection with chemical actions (heat of combination).

340. Thermal Capacity—Specific Heat.—The thermal capacity of a body is the quantity of heat required to raise the temperature of the body one degree. It is numerically equal to the mass or volume of water (according to the unit of heat employed) which would be raised one degree by the same quantity of heat.

The *specific heat* of a substance is the thermal capacity of unit mass of the substance, or, more simply, is the *ratio of the thermal capacity of the substance to that of an equal weight of water.* It is obviously independent of the unit of mass and scale of temperature adopted.

It is sometimes necessary to consider the thermal capacity of unit *volume* of a substance.[1] This will be the same as the ratio of the thermal capacity of the substance to that of an equal volume of water, if we employ as unit of heat the heat required to raise unit volume of water one degree. In discussions relating to conduction, if the foot be made the linear unit, the unit of heat employed should be the heat required to raise a cubic foot of water one degree. Thermal capacity per unit volume is, like thermal capacity per unit mass, independent of the units employed, provided they are employed consistently.

Experiment shows that nearly equal quantities of heat are required to raise a body through 1° at all temperatures between 0° C. and

---

[1] This is evidently equal to *specific heat multiplied by density;* that is, to the thermal capacity of unit mass mult[illegible] number of units of mass which are contained in a unit of volume.

100° C.; in other words, specific heat varies but very slightly with temperature between these limits. The quantity of heat which must be added to or taken from a body to raise or lower its temperature by T° will therefore be proportional to T, and will, in fact, be given by the formula

$$Q = WST,$$

where W denotes the weight of the body, and S its specific heat. The product WS is the thermal capacity of the whole body.

The specific heats of different substances differ very widely from one another. This is easily tested by the following experiment.[1]

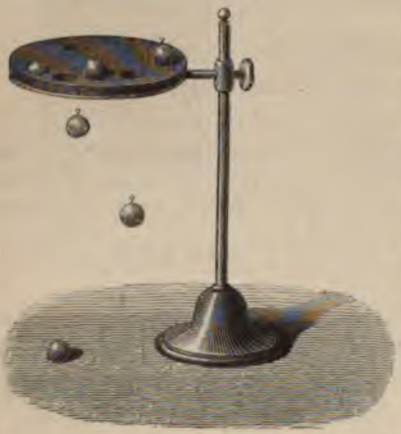


Fig. 303.—Balls Melting their way through Disc.

A number of balls, of different materials and of equal weight, are heated to the same temperature—suppose 200°—and placed upon a wax disc. Each of the balls gives up part of its heat to the wax, causing it to melt, and thus making a hole through which the ball finally drops. The balls of the greatest specific heat drop through first; thus the iron ball falls before the copper, the copper ball before the tin, &c., while the balls of lead and bismuth are much slower in their action, and, if the disc be moderately thick, never get through at all.

As another example we may take the following experiment, which serves to show the great difference between the specific heat of mercury and that of water.

A kilogramme of water at 10° and a kilogramme of mercury at 100° are poured into the same vessel and well shaken together. The temperature of the whole is then found to be about 13°, the water having gained 3 units of heat, which have been furnished by the mercury, and this loss has caused the temperature of the latter to fall through

---

[1] Critically considered, this experiment gives undue advantage to the balls of heavy material, because they have not to make such large holes for themselves as the lighter ones, in order to get through. If the balls are all made of the same *size*, we have a pretty fair test of their *thermal capacities per unit volume*.

87°. Thus we see that the specific heat of mercury is about $\frac{3}{87}$ or $\frac{1}{29}$, that of water being unity.[1]

In order to determine this element exactly, a number of minute precautions are required; in fact, the experiment just described is to be regarded merely as a means of readily exhibiting the difference between the specific heats of the two bodies. The methods of accurately determining specific heats are various; we shall describe only two of them.

341. Method by Fusion of Ice.—A hole is scooped in a solid block of ice, and a lid of the same substance is fitted over it. A body of weight W is heated to a temperature T and placed in the hole, which is immediately covered with the lid. The body, in cooling down to 0°, gives off a quantity of heat which melts some of the ice. The water thus obtained is wiped up with cotton wool, which is then weighed, having previously been weighed dry. If the weight of water thus found be denoted by m, the quantity of heat necessary to produce it is, by § 228, 79 m. But this heat is supplied by the body, and has produced in it a fall of temperature amounting to T°, which correspond to WST units of heat, S being the specific heat of the body. Hence we have $WST = 79\,m$, whence $S = \frac{79\,m}{WT}$.

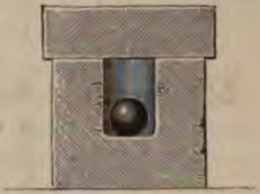


Fig. 304.—Ice-block Calorimeter.

This method is due to the Swedish philosopher Wilke, and is difficult of application in our climate. An apparatus, based on the same principle, and called the ice-calorimeter, was employed by Lavoisier and Laplace, and has recently been improved by Bunsen (*Phil. Mag.* March, 1871).

342. Method of Mixtures—Its Principle.—The method of mixtures resembles the experiment which we have already described as illustrating the difference between the specific heats of mercury and water.[2]

---

[1] The specific heat of mercury is almost exactly $\frac{1}{30}$; see table § 344.

[2] If weights w, w' of two substances whose specific heats are s, s' and temperatures t, t', are mixed, the substances being supposed not to act chemically on one another, and no heat being gained or lost externally, it is easily shown that the temperature of the mixture will be

$$\frac{wst + w's't'}{ws + w's'},$$

and, by appending additional terms to numerator and denominator, the formula becomes applicable to a mixture of any number of substances.

A body of a known weight W is raised to a fixed temperature T, and then plunged into a quantity of water of weight W′ and temperature t, which is contained in a copper vessel called a *calorimeter*. As T is supposed to exceed t, the water gains in temperature by the immersion of the body, and finally attains a maximum temperature θ, which is noted. In the change from t to θ, the water has gained a quantity of heat equal to $W'(\theta-t)$, and the body immersed has lost a quantity equal to $Wx(T-\theta)$, x being the specific heat required. Equating these two quantities, we have

$$W'(\theta-t)=Wx(T-\theta), \qquad (a)$$

whence

$$x=\frac{W'(\theta-t)}{W(T-\theta)}.$$

343. Sources of Error.—Such is the principle of the method of mixtures; but, upon closer examination, it will easily be seen that equation (a), for various reasons, must be regarded as only approximate.

I. The equation assumes that the only exchange of heat is between the body and the water, which is not actually the case.

1. The body is often contained in an envelope which cools along with it, and thus furnishes part of the heat given up.

2. The heat of the body is not given up exclusively to the water in the calorimeter, but partly to the calorimeter itself, to the thermometer, and to such other instruments as may be employed in the experiment, as, for instance, a rod to stir the liquid for the purpose of establishing uniformity of temperature throughout it.

The equation for the most general case can easily be written down. We have only to express that the quantity of heat given up by the body and its envelope is equal to that gained by the water, the calorimeter, the thermometer, and the rod.

Let W denote the weight of the body, T its initial temperature, x its specific heat, m the weight of the envelope, α its specific heat, W′ the weight of the water in the calorimeter, w the weight of the calorimeter, c its specific heat, w' the weight of the glass of the thermometer, c' its specific heat, w'' the weight of the mercury, c'' its specific heat, w''' the weight of the rod for stirring, c''' its specific heat, θ the final temperature.

Under these circumstances we evidently have the equation

$$Wx(T-\theta)+m\alpha(T-\theta)=(W'+wc+w'c'+w''c''+w'''c''')(\theta-t),$$

whence we find

$$x=\frac{(\mathrm{W}'+wc+w'c'+w''c''+w'''c''')\,(\theta-t)-ma\,(\mathrm{T}-\theta)}{\mathrm{W}\,(\mathrm{T}-\theta)}.$$

The above equation is the general type of all equations which occur in questions of this kind; the only difference that can arise is in the number of the terms, since each term represents a quantity of heat gained or lost by one of the bodies employed in the experiment.

In the above expression for x, the coefficient of $(\theta-t)$ is what is called the *water-equivalent of the calorimeter*,[1] representing, in fact, a mass of water such that, supposing it to receive exclusively all the heat given up in the experiment, a thermometer placed in it would indicate the variation of temperature actually observed. Among the elements which enter this coefficient are the specific heat of the material of the calorimeter and of the rod for stirring; these are generally made of brass, and their specific heat may be considered as known with sufficient approximation from previous experiments. The two terms connected with the thermometer may be directly determined by a previous experiment with a body whose specific heat is known.

II. The calorimeter, when heated by the body immersed in the liquid, loses a certain quantity of heat by radiation, which must be taken into account if we wish to obtain a rigorous result. For this purpose a very simple method of compensation was proposed by Rumford. It consists in lowering the initial temperature of the calorimeter below that of the surrounding air by a number of degrees equal to the excess of the final temperature above that of the surrounding air, which may easily be effected by means of a previous trial. In this case the experiment may be divided into two parts, during the first of which the calorimeter gains heat by radiation, while during the second it loses heat by the same process. As the difference of temperature between the calorimeter and the air is the same in both cases, we may consider the quantities of heat as equal. The compensation, however, is not exact, since the two periods are of unequal length, and accordingly the method adopted by most investigators has been different. This consists in determining the constant in the expression for the rate of cooling (§ 307), and employing it in the direct calculation of the number of degrees lost by radiation. In order to effect this calculation, instead of supposing the variation of temperature to be continuous, they divide the entire length of the experiment into a number of parts, during each of which they suppose the excess constant, and this method of approximation is always found to be sufficient.

---

[1] This is only another name for the *thermal capacity* of the calorimeter and its contents.

III. The calorimeter loses heat also by the supports on which it rests. This source of error can never be entirely removed, but it may easily be rendered so small as to be quite insensible. This is effected by making the supports of some substance which is a very bad conductor, and by diminishing the extent of surface of contact between them and the calorimeter.

Finally, we should ascertain carefully the initial temperature of the body, and provide against any fall of temperature in transferring it from the place of heating to the calorimeter.

344. Regnault's Apparatus.—The subject of specific heat, both for solids and liquids, has been investigated with great care by Regnault, who employed for that purpose an apparatus in which the advantages of convenience and precision are combined. The body whose specific heat is required is divided into small fragments, which are placed in a cylindrical basket G of very fine brass wire. This basket is suspended inside the steamer A, the suspending thread being fixed by

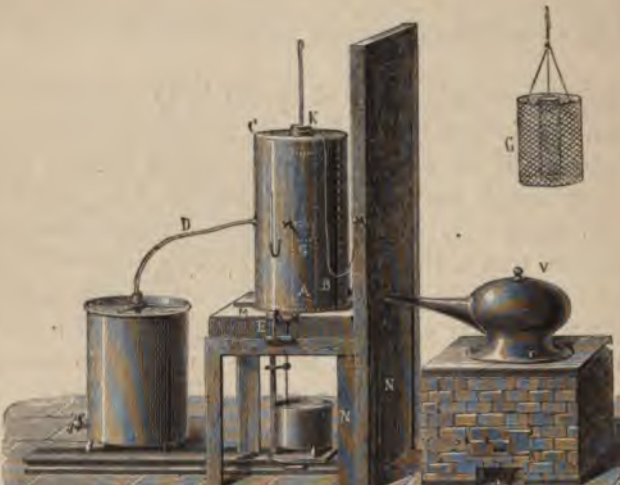


Fig. 305.—Regnault's Apparatus.

the cork K, through which passes the stem of a thermometer, the reservoir of which rests in a small tube in the centre of the basket, and made of the same material. The steamer is a double cylinder, the inside compartment B of which is filled with steam supplied by the boiler V, and afterwards conducted by the tube D into a condenser. In the bottom of the steamer is a sliding-door E, which can be drawn out when required. The outside compartment C is filled with air, to prevent the temperature of the inside from cooling by contact with the air outside.

This entire apparatus rests, by means of a sheet of cork, upon a hollow metal vessel M N, filled with water, the vertical face of which N serves as a screen to protect the calorimeter against the heat of the fire. The calorimeter itself is a vessel of very thin polished brass, resting upon silk threads stretched across the bottom of a larger vessel. This latter rests by three points upon a small wooden sled, which runs smoothly along a rail. The thermometer for measuring the temperature of the water in the calorimeter is carried by a support attached to the sled. After this explanation of the details, we proceed to indicate the course of an experiment.

The body is placed in the basket, introduced into the steamer, and there exposed to the action of the steam which is admitted from the boiler. During this part of the experiment the calorimeter is kept as far as possible from the steamer. After the lapse of an hour or two, the thermometer of the steamer remains stationary.

The calorimeter is now pushed below the sliding-door E, the door is drawn, and the basket is rapidly lowered into the calorimeter, which is immediately slid back to its former place. The basket is moved about in it for some time, and the final temperature of the water is observed. Thus we have all the elements required for the equation given above.

To determine the specific heats of liquids, a thin glass vessel is employed, in which the liquid is contained, and the effect produced by this envelope is taken into consideration in the general equation.

The same method is adopted for bodies soluble in water, or upon which water has a chemical action, some other liquid being in this case substituted, as, for instance, oil of turpentine. The specific heats of several substances are given in the following table:—

Water,	1·00000

Solids.

Antimony,	0·05077	Brass,	0·09391
Silver,	0·05601	Nickel,	0·10860
Arsenic,	0·08140	Gold,	0·03244
Bismuth,	0·03084	Phosphorus,	0·18870
Cadmium,	0·05669	Platinum,	0·03243
Charcoal,	0·24150	Lead,	0·03140
Copper,	0·09215	Plumbago,	0·21800
Diamond,	0·14680	Sulphur,	0·20259
Tin,	0·05623	Glass,	0·19768
Iron,	0·11379	Zinc,	0·09555
Iodine,	0·05412	Ice,	0·5040

Liquids.

Mercury,	0·03332	Benzine,	0·3952
Acetic acid,	0·6589	Ether,	0·5157
Alcohol at 36°	0·6735	Oil of turpentine,	0·4629

345. Great Specific Heat of Water.—This table illustrates the important fact, that, of all substances, water has the greatest specific heat; that is to say, it absorbs more heat in warming, and gives out more heat in cooling, through a given range of temperature, than an equal weight of any other substance. The quantity of heat which raises a pound of water from 0° to 100° C. would suffice to raise a pound of iron from 0° to about 900° C., that is to a bright red heat; and conversely, a pound of water in cooling from 100° to 0°, gives out as much heat as a pound of iron in cooling from 900° to 0°. This property of water is utilized in the heating of buildings by hot water, and in other familiar instances, such as the bottles of hot water used for warming beds, and railway foot-warmers.

It is of especial importance from the influence which it exerts on terrestrial temperatures. In fact, when we consider this property in conjunction with those which have been indicated in § § 228 and 247, we perceive that all the thermic modifications which water undergoes are accompanied by the evolution or absorption of remarkably large quantities of heat. If, for instance, the external temperature rises, much of the additional heat is consumed in warming the water, or in converting it into vapour, or in melting ice. If, on the other hand, the temperature falls, a large amount of heat is given up to the air by the cooling of the water, the condensation of vapour, or the formation of ice. In both cases, the change of temperature is greatly mitigated. If the water of the globe were removed, the difference of temperature between day and night, and between summer and winter, would very far exceed what are observed at present.

346. Dulong and Petit's Law.—Dulong and Petit were the first to observe that the product of the specific heat of any body, and what is called in chemistry its atomic weight, is constant. This law is of considerable importance, for it shows that atoms require each the same amount of heat to raise them through the same number of degrees. In fact, if w be the atomic weight of a body, and c its specific heat, the quantity of heat necessary for a variation of temperature of 1° is cw, and it was this product which Dulong and Petit found to be constant.

347. Specific Heats of Gases.—The limits of this treatise do not permit us to enter into the details of the complicated processes by which the specific heats of gases have been determined. It is necessary, however, to remark that, in the case of gases, two kinds of specific heat must be distinguished.

1. *Specific Heat at Constant Pressure.*—This is the quantity of heat required to raise the temperature of unit weight of the gas by one degree, when the gas is allowed to expand to such an extent that its pressure remains unchanged during the whole operation of heating.

2. *Specific Heat at Constant Volume.*—This is the amount of heat required to raise the temperature of unit weight of a gas by one degree, when the gas is compelled to retain its original volume.

The former of these exceeds the latter by the amount of heat consumed in producing the expansion.

A similar distinction exists in the case of liquids and solids, but it is not often attended to. What is always understood by specific heat in the case of these bodies is in fact their specific heat at constant pressure. The resistance of solids and liquids to compression is so enormous that a pressure of one or two atmospheres may be neglected as regards its effect upon their temperature and thermal capacity. But, in dealing with gases, the case is far otherwise, and one of the most important data for the solution of questions in gaseous mechanics is the ratio of their two specific heats.

The best experiments on the specific heats of gases are those of Regnault. They have established the two following conclusions for specific heat at constant pressure:—

(1) The specific heat (or thermal capacity per unit mass) of one and the same gas, whether simple or compound, is *the same at all pressures and temperatures.*

specific heats of different simple gases are approximately in
atio of their relative densities (§ 220), or of their atomic

weights, according to Dulong and Petit's law. This may be otherwise expressed by saying that *all simple gases have nearly the same thermal capacity per unit volume,* when at the same pressure and temperature.

The specific heat of dry air (at constant pressure), according to Regnault, is ·2375; that is to say, the thermal capacity of a given weight of air is ·2375 of that of an equal weight of water.

The above conclusions (1) and (2) are also true of specific heat at constant volume, as far as regards simple gases and air (which, being merely a mechanical mixture, obeys the same laws as a simple gas). The two following consequences have been experimentally confirmed.

(3) The *difference* between the two *thermal capacities per unit volume,* at a given pressure and temperature, is the same for all permanent gases.

(4) The *ratio* of the two specific heats is constant for all simple gases, its value being about 1·41.

It is important to remark, that the temperatures of the gases in Regnault's experiments were given by an air-thermometer, so that his result as regards the constancy of specific heat at all temperatures may be thus stated:—*If equal quantities of heat be successively added to a gas at constant pressure, the volume of the gas will increase in arithmetical progression.*

347A. Relation of Pressure to Volume when no Heat enters or escapes.—Boyle's law asserts that the density of a gas varies directly as the pressure, when the temperature is the same in the cases compared. If no heat is allowed to enter or escape, the temperature of the gas will rise when the pressure is increased, and the volume will not be so much diminished as it would be if the temperature remained constant.

Suppose that a quantity of gas at volume V, pressure P, and temperature T, receives a small addition of heat q, the gas being allowed to expand at constant pressure, so that its volume becomes $V+v$, and its temperature $T+t$, its pressure being still P.

Now let the gas be compressed without allowing any heat to enter or escape, till its volume is V as at first; and let its temperature now be $T+t+\beta t$, and its pressure $P+p$.

It is now sensibly in the same condition as if the quantity q of heat had been imparted to it without allowing any change of volume to take place; so that the same quantity q of heat which produces an elevation of temperature t at constant pressure, would produce an elevation $t+\beta t$ at constant volume. The specific heats are inversely as these elevations of temperature; hence we have

$$\frac{\text{Specific heat at constant pressure}}{\text{Specific heat at constant volume}}=1+\beta. \qquad (2)$$

To determine the change of pressure, we have

$$\frac{P+p}{P}=\frac{V+v}{V}\cdot\frac{1+\alpha\,(T+t+\beta t)}{1+\alpha\,(T+t)};\ \text{and}\ \frac{V+v}{V}=\frac{1+\alpha\,(T+t)}{1+\alpha T},$$

hence

$$\frac{P+p}{P}=\frac{1+\alpha\,(T+t+\beta t)}{1+\alpha T}=1+\frac{\alpha\,(t+\beta t)}{1+\alpha T};$$

therefore $\frac{p}{P}=\frac{\alpha\,(t+\beta t)}{1+\alpha T}$; but we have $\frac{v}{V}=\frac{\alpha t}{1+\alpha T}$;

therefore

$$\frac{p}{P}=(1+\beta)\,\frac{v}{V}, \qquad (3)$$

a result which is of great importance in connection with the velocity of sound. In fact, experiments on the velocity of sound have furnished the most precise determinations hitherto made of the value of $1+\beta$, which, as above indicated, is the ratio of specific heat at constant pressure to specific heat at constant volume, and is about 1·41.[1]

348. Heat of Fusion.—The method of mixtures may be employed to determine the quantity of heat absorbed by a body in its passage from the solid to the liquid state. For instance, a piece of ice at zero is carefully weighed and plunged into water contained in a calorimeter. The temperature of the water falls until a certain limit is attained, which is then observed. Suppose now that we have the following data:—

m the thermal capacity of the calorimeter, or the equivalent of the calorimeter in weight of water; t its initial temperature; θ its final temperature; w the weight of the ice; x the latent heat of fusion.

The heat required to melt the ice is wx, and the heat required to

---

[1] It is easily shown, by integrating equation (3), that the general relation between volume and pressure, when no heat enters or escapes, is

$$\frac{P_2}{P_1}=\left(\frac{V_1}{V_2}\right)^{1+\beta}$$

V_2 denoting the volumes at pressures P_1, P_2.

raise the water which it yields to the temperature θ is $w\,\theta$. The sum of these two quantities must be equal to $m\ (t-\theta)$, the heat given up by the calorimeter; that is,

$$w\,(x+\theta)=m\ (t-\theta),$$

from which equation x is easily found. Since this experiment necessarily occupies a considerable time, the radiation from the calorimeter must be taken into account. For this purpose a continual series of observations is taken of the temperatures indicated by the thermometer immersed in the liquid, and the quantities of heat gained or lost are estimated by the method described above (§ 343). In this way the heat of fusion of ice was fixed by Laprovostaye and Desains at 79·25 Centigrade, which is equivalent to 142·65 Fahrenheit.

When the body melts at a high temperature, the method is reversed; the body is first melted, and then immersed in the calorimeter. In doing this, precautions must be taken to prevent the vaporization of a portion of the water; for instance, the body may be inclosed in a small thin box which is not completely opened until towards the close of the experiment. Suppose we have W, the equivalent of the calorimeter in water; t its initial temperature; θ its final temperature; w the weight of the body; T its initial temperature; T′ its melting-point; c its specific heat in the solid state; c' its specific heat in the liquid state; from these data the equation will evidently be

$$\mathrm{W}\ (\theta-t)=wx+wc'\ (\mathrm{T}-\mathrm{T}')+wc\ (\mathrm{T}'-\theta),$$

neglecting the correction for radiation, which can be determined by the ordinary methods.

One of the quantities which enter into this equation is the specific heat of the body in the solid state, which may be considered as known. The specific heat of the body in the liquid state may be deduced by combining this equation with another of the same kind, in which the initial temperature of the melted body is different. In the case of bodies which, like mercury and bromine, are liquid at ordinary temperatures, the specific heat in the solid state can be found by a similar but inverse process.

The following table gives the heats of fusion of several substances, together with their specific heats in both states.

Substances.	Melting-point.	Specific Heats		Latent Heat of Fusion.
		In the Solid State.	In the Liquid State.	
Water, ...	0°	·5040	1·0000	79·250
Phosphorus, . .	44·20	·2000	·2000	5·400
Sulphur, ...	111	·2020	·2340	9·368
Bromine, ...	−7·32	·0840	·1670	16·185
Tin, ...	232	·0560	·0640	14·252
Bismuth, ...	266	·0308	·0363	12·640
Lead, ...	326	·0314	·0402	5·369
Mercury, ...	−39	·0319	·0333	2·820

349. Heat of Evaporation.—The latent heat of evaporation of water, and of some other liquids, can be determined by means of Despretz's apparatus, which is shown in Fig. 306.

The liquid is boiled in a retort C, which is connected with a worm S surrounded by cold water, and terminating in the reservoir R. The vapour is condensed in the worm, and collects in the reservoir, whence it can be drawn by means of the stop-cock *r*. The tube T, which is fitted with a stop-cock *r*′, serves to establish communication between the reservoir and the atmosphere, or between the reservoir and a space where a fixed pressure is maintained, so as to produce ebullition at any temperature required, which is indicated by the thermo-

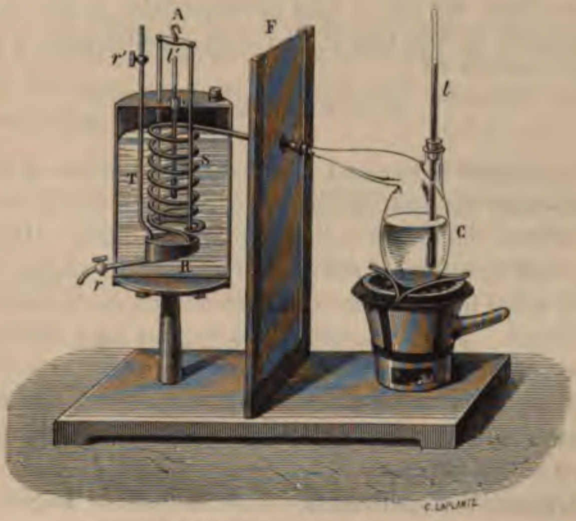


Fig. 306.—Despretz's Apparatus.

meter t. A is an agitator for keeping the water at a uniform temperature, which is indicated by the thermometer t'.

In using the apparatus, the first step is to boil the liquid in the retort, and when it is in active ebullition, it is put in communication with the worm. The temperature of the calorimeter has previously been lowered a certain number of degrees below that of the surrounding air, and the experiment ceases when it has risen to the same number of degrees above. The compensation may thus be considered as complete, since the rate of heating is nearly uniform.

If W be the equivalent of the calorimeter in water, t its initial temperature, θ its final temperature; then the quantity of heat gained by it is $W(\theta-t)$. This heat comes partly from the latent heat disengaged at the moment of condensation of the vapour, partly from the loss of temperature of the condensed water, which sinks from T, the boiling-point of the liquid, to the temperature of the calorimeter. If, then, x denote the latent heat of evaporation, w the weight of the liquid collected in the box R, and c its specific heat, we have the equation

$$W(\theta-t)=wx+wc(T-\theta).$$

This experiment is exposed to some serious causes of error. The calorimeter may be heated by radiation from the screen F which protects it from the direct radiation of the furnace. Heat may also be propagated by means of the neck of the retort. Again, the vapour is not *dry* when it passes into the worm, but carries with it small drops of liquid. Finally, some of the vapour may be condensed at the top of the retort, and so pass into the worm in a liquid state. This last objection is partly removed by sloping the neck of the retort upwards from the fire, but it sometimes happens that this precaution is not sufficient.

350. Regnault's Experiments.—The labours of Regnault in connection with the subject of latent heat are of the greatest importance, and have resulted in the elaboration of a method in which all these sources of error are entirely removed. The results obtained by him are the following:—

The quantity of heat required to convert a kilogramme of water at 100° into vapour, without change of temperature, is 537 kilogramme-degrees or calories.

If the water were originally at zero, the total amount of heat required to convert it into vapour at 100° would be 637 calories—

100 to raise it to 100°, and 537 more to convert it into vapour. It is this total amount which is most important to know in the applications of heat in the arts.

In general, if Q denote the total quantity of heat[1] required to transform water at zero into vapour at the temperature T, the value of Q may be deduced with great exactness from the following equation:—

$$Q = 606{\cdot}5 + {\cdot}305\,T. \qquad (a)$$

From what we have said above, it will be seen that if λ denote the latent heat of evaporation at temperature T, we must have

$$Q = \lambda + T,$$

whence, by substituting for Q in (*a*), we have

$$\lambda = 606{\cdot}5 - {\cdot}695\,T. \qquad (b)$$

From (*a*) we can find the total heat for any given temperature, and from (*b*) the latent heat of evaporation at any given temperature. The results for every tenth degree between 0° and 230° are given in the following table:—

Temperatures Centigrade.	Latent Heat.	Total Heat.	Temperatures Centigrade.	Latent Heat.	Total Heat.
0° . . .	606	606	120°. . .	522	642
10 . . .	600	610	130 . . .	515	645
20 . . .	593	613	140 . . .	508	648
30 . . .	586	616	150 . . .	501	651
40 . . .	579	619	160 . . .	494	654
50 . . .	572	622	170 . . .	486	656
60 . . .	565	625	180 . . .	479	659
70 . . .	558	628	190 . . .	472	662
80 . . .	551	631	200 . . .	464	664
90 . . .	544	634	210 . . .	457	667
100 . . .	537	637	220 . . .	449	669
110 . . .	529	639	230 . . .	442	672

To reduce latent heat and total heat from the Centigrade to the Fahrenheit scale, we must multiply by $\frac{9}{5}$. Thus the latent and total heat of steam at 212° F. are 966·6 and 1146·6. We subjoin a table, taken from the researches of Favre and Silbermann, giving the latent heat of evaporation of a number of liquids at the temperature of their boiling-point, referred to the Centigrade scale:—

---

[1] Called by Regnau [illegible] saturated vapour at T°, or the total heat of vaporization at T°.

	Boiling-point.	Latent Heat.		Boiling-point.	Latent Heat.
Wood-spirit, . . .	66·5	264	Acetic acid, . . .	120°	102
Absolute alcohol, . .	78	208	Butyric acid, . . .	164	115
Valeric alcohol, . .	78	121	Valeric acid, . . .	175	104
Ether, ...	38	91	Acetic ether, . . .	74	100
Ethal, ...	38	58	Oil of turpentine, . .	156	69
Valeric ether, . . .	113·5	113·5	Essence of citron, .	165	70
Formic acid, . . .	100	169			

351. Heat Disengaged in Chemical Combinations.—A very convenient apparatus has been invented by Favre and Silbermann for measuring the heat given off in chemical reactions.[1] It is a kind of large mercurial thermometer (Fig. 307), the reservoir R of which is made of iron, and contains one or more cylindrical openings similar to that shown at m. Into these are fitted tubes of glass or platinum, in which the chemical reaction takes place. One of the substances is introduced first, and the other, which is liquid, is then added by means of a pipette bent at B, and containing the liquid in a globe, as shown in the figure. This is effected by raising the pipette into the position indicated by the dotted lines in the figure.

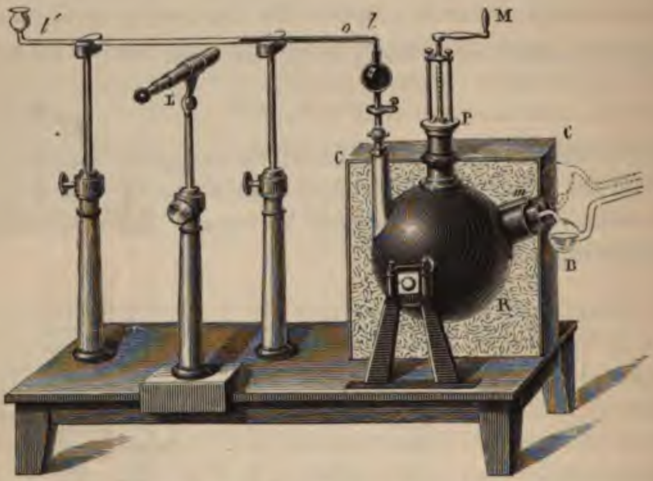


Fig. 307.—Calorimeter of Favre and Silbermann.

In the upper part of the reservoir is an opening fitted with a tube containing a steel plunger P, which descends into the mass of mercury, and can be screwed down or up by turning the handle M. To prepare the apparatus for use, the plunger is so adjusted that the mercury stands at the zero-point of the graduated tube *tt′*, the reaction is then allowed to take place, and the movement of the mercurial column is observed with the telescope L. In order to measure the quantity of heat corresponding to this displacement, a known weight of hot water is introduced into the reservoir, and allowed to give up its heat to the mercury; the displacement of the mercurial column is then observed, and since the quantity of heat corresponding to this displacement is known, that corresponding to any other displacement can easily be calculated. The iron reservoir is inclosed in a box filled with wadding or some other non-conducting material.[1]

---

[1] Chemical actions are called *reactions*, and a substance which acts chemically is called a *reagent*. The names are awkward, but are in general use.

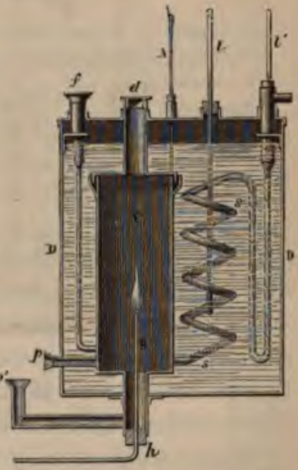


Fig. 308.—Dulong's Calorimeter for Combustion.

When the chemical reaction takes the form of combustion, a different arrangement is necessary. An apparatus of great perfection has been devised by Favre and Silbermann for this purpose, but it is of too complex a construction to be described here. A sufficiently accurate idea of the general method adopted in these cases will be obtained by a study of the much simpler apparatus employed for the same purpose by Dulong.

It consists of a combustion-chamber C surrounded by the water contained in a calorimeter D, in which moves an agitator whose stem is shown at A. The combustible substance, if it be a gas, is conducted into the chamber through the tube *h*, and the oxygen necessary for its combustion enters by one of the tubes *f* or *p′*. The products of combustion pass through the worm *s*, and finally escape, but not until they have fallen to the temperature of the water in the calorimeter. This condition is necessary to the exactness of the result, and its precise fulfilment is verified by observing the temperatures indicated by the thermometers t and t', the former of which gives the temperature of the water, and the latter that of the products of combustion at their exit. These two temperatures should always agree. The progress of the combustion is observed through the opening p, which is closed by a piece of glass. Some of the results obtained by this method are given in the following table, the combustion being supposed to take place in oxygen, with the exception of the second example on the list

---

[1] In the mode of experimentation adopted by Dr. Andrews, the combination takes place in a thin copper vessel inclosed in a calorimeter of water to which it gives up its heat; and the rise of temperature in the water is observed with a very delicate thermometer, the water being agitated either by stirring with a glass rod or by making the whole apparatus revolve about a horizon

In experimenting [illegible] mbustion, the oxygen and the substance to be burned are introduced in [illegible] l, which is inclosed in the calorimeter as above, [illegible] ans of electricity.

Heats of Combustion.[1]

(Referred to the Centigrade Scale.)

Hydrogen,	34,462	Soft sulphur,	2,258
Hydrogen with chlorine,	23,783	Sulphide of carbon,	3,400
Carbonic oxide,	3,403	Olefiant gas,	11,857
Marsh-gas,	13,063	Ether,	9,028
Charcoal,	8,080	Alcohol,	7,184
Graphite,	7,797	Stearic acid,	9,616
Diamond,	7,770	Oil of turpentine,	10,852
Native sulphur,	2,261	Olive-oil,	9,862

Of all substances hydrogen possesses by far the greatest heat of combustion. This fact accounts for the intense heating effects which can be obtained with the oxy-hydrogen blowpipe, in which an annular jet of hydrogen is completely burned by means of a central jet of oxygen. It is to be observed that the heat of combination observed by the above methods includes the heating or cooling effect of the changes of volume which usually accompany chemical combination.

---

[1] These numbers denote the number of times its own weight of water which would be raised one degree Centigrade by the heat evolved in the combustion of the substance. For example, the combustion of a pound of charcoal gives out enough heat to raise 8080 pounds of water one degree.

CHAPTER XXXII.

THERMO-DYNAMICS.

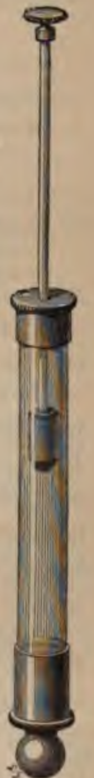


Fig. 310. Pneumatic Tinder-box.

354. Connection between Heat and Work.—That heat can be made to produce work is evident when we consider that the work done by steam-engines and other heat-engines is due to this source.

Conversely, by means of work we can produce heat. Fig. 310 represents an apparatus sometimes called the pneumatic tinder-box, consisting of a piston working tightly in a glass barrel. If a piece of gun-cotton be fixed in the cavity of the piston, and the air be then suddenly compressed, so much heat will be developed as to inflame the gun-cotton.

A singular explanation of this effect was at one time put forward. It was maintained that heat or *caloric* was a kind of imponderable fluid, which, when introduced into a body, produced at once an increase of volume and an elevation of temperature. If, then, the body was compressed, the caloric which had served to dilate it was, so to speak, *squeezed out*,[1] and hence the development of heat. An immediate consequence of this theory is that heat cannot be increased or diminished in quantity, but that any addition to the quantity of heat in one part of a system must be compensated by a corresponding loss in another part. But we know that there are cases in which heat is produced by two bodies in contact, without our being able to observe any traces of this compensating process. An instance of this is the production of heat by friction.

355. Heat produced by Friction.—Friction is a well-known source of heat. Savages are said to obtain fire by rubbing two pieces of dry wood together. The friction between the wheel and axle in railway-carriages frequently produces the same effect, when they have been insufficiently greased; and the stoppage of a train by applying a brake to the wheels usually produces a shower of sparks.

---

[1] In [illegible]ls, the thermal capacity of the body was supposed to be diminis[illegible] amount of heat contained in it, without undergoing any increase, was abl[illegible]gher temperature.

The production of heat by friction may be readily exemplified by the following experiment, due to Tyndall. A glass tube containing water (Fig. 311), and closed by a cork, can be rotated rapidly about its axis. While thus rotating, it is pressed by two pieces of wood, covered with leather. The water is gradually warmed, and finally enters into ebullition, when the cork is driven out, followed by a jet of steam. Friction, then, may produce an intense heating of the bodies rubbed together, without any corresponding loss of heat elsewhere.

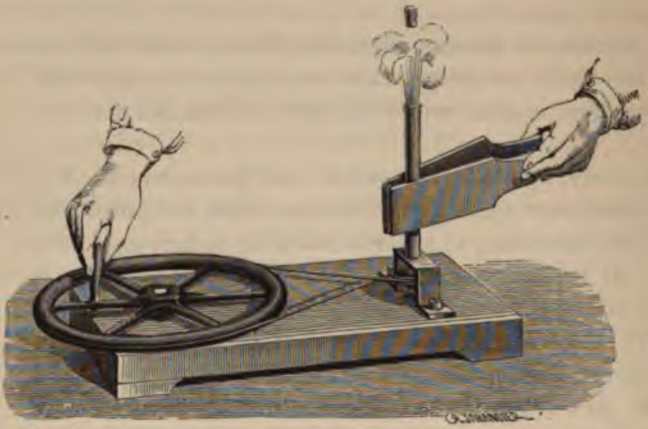


Fig. 311.—Heat produced by Friction.

At the close of last century, Count Rumford (an American in the service of the Bavarian government) called attention to the enormous amount of heat generated in the boring of cannon, and found, in a special experiment, that a cylinder of gun-metal was raised from the temperature of 60° F. to that of 130° F. by the friction of a blunt steel borer, during the abrasion of a weight of metal equal to about $\frac{1}{950}$ of the whole mass of the cylinder. In another experiment, he surrounded the gun by water (which was prevented from entering the bore), and, by continuing the operation of boring for $2\frac{1}{2}$ hours, he made this water boil. In reasoning from these experiments, he strenuously maintained that heat cannot be a material substance, but must consist in motion.

The advocates of the caloric theory endeavoured to account for these effects by asserting that caloric, which was latent in the metal when united in one solid mass, had been forced out and rendered sensible by the process of disintegration under heavy pressure. This supposition was entirely gratuitous, no difference having ever been detected between the properties of entire and of comminuted metal as regards thermal capacity; and, to account for the observed effect, the latent heat thus supposed to be rendered sensible in the abrasion of a given weight of metal, must be sufficient to raise 950 × 70, that is 66,500 times its own weight of metal through 1°.

Yet, strange to say, the caloric theory survived this exposure of its weakness, and the, if possible, still more conclusive experiment of Sir Humphrey Davy, who showed that two pieces of ice, when rubbed together, were converted into water, a change which involves not the evolution but the absorption of latent heat, and which cannot be explained by diminution of thermal capacity, since the specific heat of water is much greater than that of ice.

Davy, like Rumford, maintained that heat consisted in motion, and the same view was maintained by Dr. Thos. Young; but the doctrine of caloric nevertheless continued to be generally adopted until about the year 1840, since which time, the experiments of Joule, the eloquent advocacy of Meyer, and the mathematical deductions of Thomson, Rankine, and Clausius, have completely established the mechanical theory of heat, and built up an accurate science of thermodynamics.

356. Foucault's Experiment.—The relations existing between electrical and thermal phenomena had considerable influence in leading to correct views regarding the nature of heat. An experiment devised by Foucault illustrates these relations, and at the same time furnishes a fresh example of the production of heat by the performance of mechanical work.

The apparatus consists (Fig. 312) of a copper disc which can be made to rotate with great rapidity by means of a system of toothed wheels. The motion is so free that a very slight force is sufficient to maintain it. The disc rotates between two pieces of iron, constituting the ar[illegible] one of those temporary magnets which are obtained by [illegible] electric current (called electro-magnets). If, while the disc is turning, the current is made to pass, the armatures become strongly magnetized, and a peculiar action takes place between them and the disc, consisting in the formation of induced currents in the latter, accompanied by a resistance to motion. As long as the magnetization is continued, a considerable effort is necessary to maintain the rotation of the disc; and if the rotation be continued for two or three minutes, the disc will be found to have risen some 50° or 60° C. in temperature, the heat thus acquired by the disc being the equivalent of the work done in maintaining the motion. It is to be understood that, in this experiment, the rotating disc does not touch the armatures; the resistance which it experiences is due entirely to invisible agencies.

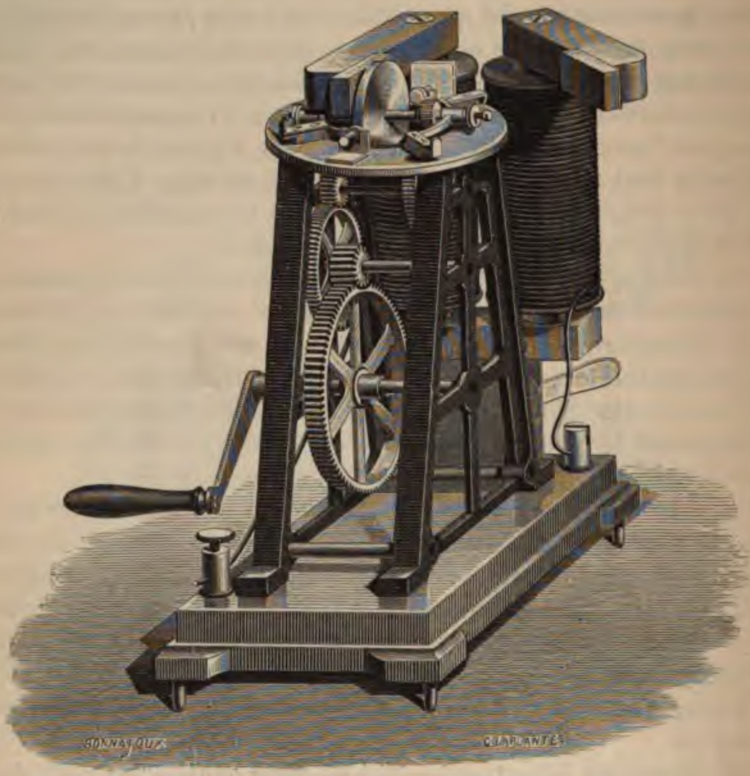


Fig. 312.—Foucault's Apparatus.

The experiment may be varied by setting the disc in very rapid rotation, while no current is passing, then leaving it to itself, and immediately afterwards causing the current to pass. The result will be, that the disc will be brought to rest almost instantaneously, and will undergo a very slight elevation of temperature, the heat gained being the equivalent of the motion which is destroyed.

357. Mechanical Equivalent of Heat.—The most precise determination yet made of the numerical relation subsisting between heat and mechanical work was obtained by the following experiment of Joule. He constructed an agitator which is somewhat imperfectly represented in Fig. 313, consisting of a vertical shaft carrying several sets of paddles revolving between stationary vanes, these latter serving to prevent the liquid in the vessel from being bodily whirled in the direction of rotation. The vessel was filled with water, and the agitator was made to revolve by means of a cord, wound round the upper part of the shaft, carried over a pulley, and attached to a weight, which by its descent drove the agitator, and furnished a measure of the work done. The pulley was mounted on friction-wheels, and the weight could be wound up without moving the paddles. When all corrections had been applied, it was found that the heat communicated to the water by the agitation amounted to one pound-degree Fahrenheit for every 772 foot-pounds of work spent in producing it. This result was verified by various other forms of experiment, and may be assumed to be correct within about one foot-pound. The experiments were made at Manchester, where

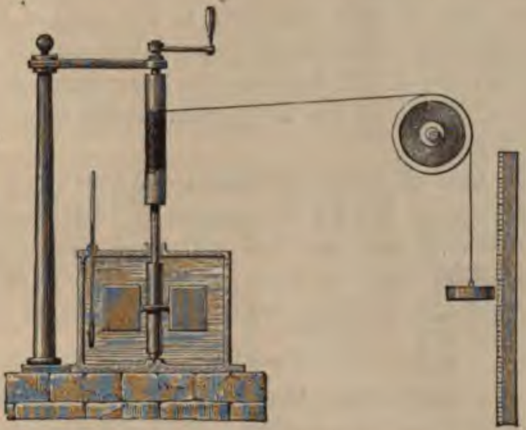


Fig. 313.—Determination of the Mechanical Equivalent of Heat.

g is 32·194, and it is to be borne in mind that a foot-pound does not denote precisely the same amount of work at all places on the earth's surface, but varies in direct proportion to the intensity of gravity. The difference in its value in passing from one place to another on the earth is, however, not greater than the probable error of the number 772. We may therefore, with about as much accuracy as is warranted by the present state of our knowledge, assert that the energy comprised in one pound-degree Fahrenheit is about 772 terrestrial foot-pounds.[1]

The mechanical equivalent of the pound-degree Centigrade is $\frac{9}{5}$ of this, or about 1390 foot-pounds.

The number 772 or 1390, according to the scale of temperature adopted, is commonly called *Joule's equivalent*, and is denoted in formulæ by the letter J. If we take the kilogramme-degree Centigrade for unit of heat, and the kilogrammetre for unit of work, the value of J will be 424.

357 A. First Law of Thermo-dynamics.—Whenever work is performed by the agency of heat, an amount of heat disappears equivalent to the work performed; and whenever mechanical work is spent in generating heat, the heat generated is equivalent to the work thus spent; that is to say, we have in both cases

$$W = JH;$$

W denoting the work, H the heat, and J Joule's equivalent. This is called the *first law of thermo-dynamics*, and it is a particular case of the great natural law (§ 53K) which asserts that energy may be transmuted, but is never created or destroyed.

It may be well to remark here that work is not energy, but is rather the process by which energy is transmuted (§ 53J), amount of work being measured by the amount of energy transmuted. Whenever work is done, it leaves an effect behind it in the shape of energy of some kind or other, equal in amount to the energy consumed in performing the work, or, in other words, equal to the work itself.

As regards the nature of heat, there can be little doubt that heat properly so called, that is sensible as distinguished from latent heat, consists in some kind of motion, and that quantity of heat is quantity of energy of motion, or kinetic energy (§ 53I), whereas latent heat consists in energy of position or potential energy (§ 53J).

---

[1] In absolute units of work, of which a foot-pound contains g, the equivalent of a pound-degree Fahrenheit is $772 \times 32·194 = 24854$, which is within less than 1 per cent. of 25,000. Hence the heat-equivalent of the kinetic energy of a mass of m pounds moving with a velocity of v feet per second is approximately $\frac{1}{2}mv^2 \div 25000$, or $2\,mv^2 \div 100000$.

We have already had, in the experiments of Rumford, Davy, Foucault, and Joule, some examples of transmutation of energy; but it will be instructive to consider some additional instances.

When a steam-engine is employed in hauling up coals from a pit, an amount of heat is destroyed in the engine equivalent to the energy of position which is gained by the coal.

In the propulsion of a steam-boat with uniform velocity, or in the drawing of a railway train with uniform velocity on a level, there is no gain of potential energy, neither is there, as far as the vessel or train is concerned, any gain of kinetic energy. In the case of the steamer, the immediate effect consists chiefly in the agitation of the water, which involves the generation of kinetic energy; and the ultimate effect of this is a warming of the water, as in Joule's experiment. In the case of the train, the work done in maintaining the motion is spent in friction and concussions, both of which operations give heat as the ultimate effect. Here, then, we have two instances in which heat, after going through various transformations, reappears as heat at a lower temperature.

In starting a train on a level, the heat destroyed in the engine finds its equivalent mainly in the energy of motion gained by the train; and this energy can again be transformed into heat by turning off the steam and applying brakes to the wheels.

When a cannon-ball is fired against an armour plate, it is heated red-hot if it fails to penetrate the plate, the energy of the moving ball being in this case obviously converted into heat. If the plate is penetrated, and the ball lodges in the wooden backing, or in a bank of earth, the ball will not be so much heated, although the total amount of heat generated must still be equivalent to the energy of motion destroyed. The ruptured materials, in fact, receive a large portion of the heat. The heat produced in the rupture of iron is well illustrated by punching and planing machines, the pieces of iron punched out of a plate, or the shavings planed off it, being so hot that they can scarcely be touched, although the movements of the punch and plane are exceedingly slow. The heat gained by the iron is, in fact, the equivalent of the work performed, and this work is considerable on account of the great force required.

357B. Heat Lost in Expansion.—The difference between the specific heat of a gas at constant pressure and at constant volume, is almost exactly the equivalent of the work which the gas at constant pressure performs in pushing back the surrounding atmosphere. Joule immersed two equal vessels in water, one of them containing highly-compressed air, and the other being exhausted; and when they were both at the temperature of the water he opened a stop-cock which placed the vessels in communication. The compressed air thus expanded to double its volume, but the temperature of the surrounding water was unaltered, the heat converted into energy of motion by the expansion being, in fact, compensated by the heat generated in the destruction of this motion in the previously vacuous vessel. This experiment shows that, when air expands without having to overcome external resistances, its temperature is not sensibly changed by the expansion.

Suppose we have a cylinder whose internal section is a square decimetre, and that a piston travelling in this cylinder is pushed outwards by the expansion of air in the cylinder. Let the air be initially at 0° C., and occupy 1 decimetre in length of the cylinder, so that its volume at this temperature is a cubic decimetre, and let this air be expanded at the constant pressure of 760 mm. by the addition of heat, until it occupies double its initial volume, and has therefore pushed the piston a distance of 1 decimetre. Since air expands by $\frac{1}{273}$ of its volume at 0° for each degree, the final temperature will, in this case, be 273° C., and since the specific heat of air at constant pressure is ·237, and the weight of the air is 1·293 gramme, the heat taken up by the air is

$$273 \times \cdot 237 \times 1 \cdot 293 = 83 \cdot 66 \text{ gramme-degrees.}$$

Now the pressure of 760 mm. is equivalent to 1·033 kilogrammes per square centimetre; hence the total pressure resisting the advance of the piston is 103·3 kilogrammes, which is overcome through a distance of 1 decimetre, so that the work done against atmospheric resistance is 10·33 kilogrammetres.

Joule's equivalent for a kilogramme-degree is 424 kilogrammetres. The heat-equivalent of the work done in the present case is therefore $\frac{10 \cdot 33}{424} = \cdot 02436$ kilogramme-degree $= 24 \cdot 36$ gramme-degrees.

Hence, of the whole heat 83·66 received by the air in the cylinder, 24·36 has been spent in doing external work, leaving 59·3 as the amount which would have sufficed to raise the air to the same temperature if no external work had been performed. Now the ratio of 83·66 to 59·3 is 1·41, which, as we have already seen (§ 347), is the ratio of specific heat at constant pressure to specific heat at constant volume.

In the case of air and perfect gases, the heat gained by compression or lost in expansion is almost the exact equivalent of the external work performed.

In view of these facts, the specific heat of a gas at constant volume is often called the *true specific heat* of the gas. The heat required to produce a given change of temperature in a gas, when its volume changes in any specified way, may be computed to a very close approximation by calculating the work done by the gas against external resistances during its change of volume, and adding the heat-equivalent of this work to the heat which would have produced the same change of temperature at constant volume. The true specific heat of air in this sense is ·168.

358. Thermic Engines.—In every form of thermic engine, work is obtained by means of expansion produced by heat, the force of expansion being usually applied by admitting a hot elastic fluid to press alternately on opposite sides of a piston travelling in a cylinder. Of the heat received by the elastic fluid from the furnace, a part leaks out by conduction through the sides of the containing vessels, another part is carried out by the fluid when it escapes into the air or into the condenser, the fluid thus escaping being always at a temperature lower than that at which it entered the cylinder, but higher than that of the air or condenser into which it escapes; but a third part has disappeared altogether, and ceased to exist as heat, having been spent in the performance of work. This third part is the exact equivalent of the work performed by the elastic fluid in driving the piston,[1] and may therefore be called the *heat utilized*, or the *heat converted*.

The *efficiency of an engine* may be measured by *the ratio of the heat thus converted to the whole amount of heat which enters the engine;* and we shall use the word *efficiency* in this sense.

358A. Carnot's Investigations.—The first approach to an exact science of thermo-dynamics was made by Carnot in 1824. By reasoning based on the theory which regards heat as a substance, but which can be modified so as to remain conclusive when heat is regarded as a form of energy, he established the following principles:—

---

[1] [illegible] tive work is done by the fluid in any part of the stroke (that is, if the piston [illegible] fluid), the algebraic sum of w [illegible] be taken.

I. *The thermal agency by which mechanical effect may be obtained is the transference of heat from one body to another at a lower temperature.* These two bodies he calls the *source* and the *refrigerator.* Adopting the view generally received at that time regarding the nature of heat, he supposed that all the heat received by an engine was given out by it again as heat; so that, if all lateral escape was prevented, all the heat drawn by the engine from the source was given by the engine to the refrigerator, just as the water which by its descent turns a mill-wheel, runs off in undiminished quantity at a lower level. We now know that, when heat is let down through an engine from a higher to a lower temperature, it is diminished in amount by the equivalent of the work done by the engine against external resistances.

He further shows that the amount of work which can be obtained by letting down a given quantity of heat—or, as we should say with our present knowledge, by partly letting it down and partly consuming it in work, is increased by raising the temperature of the source, or by lowering the temperature of the refrigerator; and establishes the following important principle:—

II. *A perfect thermo-dynamic engine is such that, whatever amount of mechanical effect it can derive from a certain thermal agency; if an equal amount be spent in working it backwards, an equal reverse thermal effect will be produced.* This is often expressed by saying that a *completely reversible engine* is a *perfect engine.*

By a *perfect engine* is here meant an engine which possesses the maximum of efficiency compatible with the given temperatures of its source and refrigerator; and Carnot here asserts that all completely reversible engines attain this maximum of efficiency. The proof of this important principle, when adapted to the present state of our knowledge, is as follows:—

Let there be two thermo-dynamic engines, A and B, working between the same source and refrigerator; and let A be completely reversible. Let the efficiency of A be m, so that, of the quantity Q of heat which it draws from the source, it converts $m\,Q$ into mechanical effect, and gives $Q-m\,Q$ to the refrigerator, when worked forwards. Accordingly, when worked backwards, with the help of work $m\,Q$ applied to it from without, it takes $Q-m\,Q$ from the refrigerator, and gives Q to the source.

In like manner, let the efficiency of B be m', so that, of heat Q' which it draws from the source, it converts $m'Q'$ into mechanical effect, and gives $Q'-m'Q'$ to the refrigerator.

Let this engine be worked forwards, and A backwards. Then, upon the whole, heat to the amount $Q'-Q$ is drawn from the source, heat $m'Q'-m\,Q$ is converted into mechanical effect, and heat $Q'-Q-(m'Q'-m\,Q)$ is given to the refrigerator.

If we make $m'Q'=m\,Q$, that is, if we suppose the external effect to be nothing, heat to the amount $Q'-Q$ or $\left(\frac{m}{m'}-1\right)Q$ is carried from the source to the refrigerator, if m be greater than m', that is, if the reversible engine be the more efficient of the two. If the other engine be the more efficient, heat to the amount $\left(1-\frac{m}{m'}\right)Q$ is transferred from the refrigerator to the source, or heat pumps itself up from a colder to a warmer body, and *that* by means of a machine which is self-acting, for B does work which is just sufficient to drive A. Such a result we are entitled to assume impossible, therefore B cannot be more efficient than A.

Another proof is obtained by making $Q'=Q$. The source then neither gains nor loses heat, and the refrigerator gains $(m-m')\,Q$, which is derived from work performed upon the combined engine from without, if A be more efficient than B. If B were the more efficient of the two, the refrigerator would lose heat to the amount $(m'-m)\,Q$, which would yield its full equivalent of external work, and thus a machine would be kept going and doing external work by means of heat drawn from the coldest body in its neighbourhood, a result which cannot be admitted to be possible.

358 B. Second Law of Thermo-dynamics.—It follows, from the principle thus established, that all *reversible engines* with the same temperatures of source and refrigerator have the same efficiency, whether the working substance employed in them be steam, air, or any other material, gaseous, liquid, or solid. Hence we can lay down the following law, which is called the second law of thermo-dynamics: *the efficiency of a completely reversible engine is independent of the nature of the working substance, and depends only on the temperatures at which the engine takes in and gives out heat; and the efficiency of such an engine is the limit of possible efficiency for any engine.*

As appendices to this law it has been further established:

when one of the two temperatures is fixed, the efficiency ortional to the difference between the two, provided this difference is very small. This holds good for all scales of temperature.

2. From calculations relating to an imaginary engine of special simplicity, in which a permanent gas is the working substance, it has been determined that the efficiency of a reversible engine is approximately $\frac{T-T'}{T}$, T denoting the upper, and T′ the lower temperature between which the engine works, reckoned from absolute zero (§ 219 A), on the air-thermometer. This is more easily remembered when stated in the following more symmetrical form. Let Q denote the quantity of heat taken in at the absolute temperature T, Q′ the quantity given out at the absolute temperature T′, and consequently Q—Q′ the heat converted into mechanical effect, then we shall have approximately

$$\frac{Q}{T} = \frac{Q'}{T'} = \frac{Q-Q'}{T-T'}.$$

358c. Absolute Scale of Temperature.—In ordinary thermometers, temperatures are measured by the apparent expansion of a liquid in a glass envelope. If two thermometers are constructed, one with mercury and the other with alcohol for its liquid, it is obviously possible to make their indications agree at two fixed temperatures. If, however, the volume of the tube intervening between the two fixed points thus determined be divided into the same number of equal parts in the two instruments, and the divisions be numbered as degrees of temperature, the two instruments will give different indications if plunged in the same bath at an intermediate temperature, and they will also differ at temperatures lying beyond the two fixed points. It is a simple matter to test equality of temperature, but it is far from simple to decide upon a test of equal differences of temperature. Different liquids expand not only by different amounts but by amounts which are not proportional, no two liquids being in this respect in agreement.

In the case of permanent gases expanding under constant pressure, the discordances are much less, and may, in ordinary circumstances, be neglected. Hence gases would seem to be indicated by nature as the proper substances by which to measure temperature, if differences of temperature are to be measured by differences of volume.

It is also possible to establish a scale of temperature by assuming that some one substance rises by equal increments of temperature on receiving successive equal additions of heat; in other words, by making some one substance the standard of reference for specific heat, and assuming the specific heat of this substance to be the same at all temperatures. Here, again, the scale would be different according to the liquid chosen. A mixture of equal weights of water at 0° C. and 100° C. will not have precisely the same temperature as a mixture of equal weights of mercury at these temperatures. If, however, we resort to permanent gases, we find again a very close agreement, so that, if one gas be assumed to have the same specific heat at all temperatures (whether at constant volume or at constant pressure), the specific heat of any other permanent gas will also be sensibly independent of temperature. More than this;—the measurement of temperature by assuming the specific heats of permanent gases to be constant, agrees almost exactly with the measurement of temperature by the expansion of permanent gases. For, as we have seen (§ 347), a permanent gas under constant pressure has its volume increased by equal amounts on receiving successive equal additions of heat.

The air-thermometer, or gas-thermometer, then, has a greatly superior claim to the mercury thermometer to be considered as furnishing a natural standard of temperature.

But a scale which is not only sensibly but absolutely independent of the peculiarities of particular substances, is obtained by *defining temperature in such a sense as to make appendix* (2) *to the second law of thermo-dynamics rigorously exact.* According to this system, the ratio of any two temperatures is the ratio of the two quantities of heat which would be drawn from the source and supplied to the refrigerator by a completely reversible thermo-dynamic engine working between these temperatures. This ratio will be rigorously the same, whatever the working substance in the engine may be, and whether it be solid, liquid, or gaseous.

358 D. Heat required for Change of Volume and Temperature.—The amount of heat which must be imparted to a body to enable it to pass from one condition, as regards volume and temperature, to another, is not a definite quantity, but depends upon the course by which the transition is effected. It is, in fact, the sum of two quantities, one of them being *the heat which would be required if the transition were made without external work*—as in Joule's experiment of the expansion of compressed air into a vacuous vessel—and [illegible]r being *the heat equivalent to the external work which the* [illegible]s *in making the transiti*[illegible] As regards the first of these quantities, its amount, in the case of permanent gases, depends almost entirely upon the difference between the initial and final temperatures, being sensibly independent of the change of volume, as Joule's experiment shows. In the case of liquids and solids, its amount depends, to a very large extent, upon the change of volume, so that, if the expansion which heat tends to produce is forcibly prevented, the quantity of heat required to produce a given rise of temperature is greatly diminished. This contrast is sometimes expressed by saying that expansion by heat involves a large amount of internal work in the case of liquids and solids, and an exceedingly small amount in the case of gases; but the phrase *internal work* has not as yet acquired any very precise meaning.

External work performed against uniform hydrostatic or pneumatic pressure, may be computed by *multiplying the increase of volume by the pressure per unit area.* For, if we suppose the expanding body to be immersed in an incompressible fluid without weight, confined in a cylinder by means of a movable piston under constant pressure, the work done by the expanding body will be spent in driving back the piston. Let A be the area of the piston, x the distance it is pushed back, and p the pressure per unit area. Then the increment of volume is $\mathrm{A}x$, and the work done is the product of the force $p\mathrm{A}$ by the distance x, which is the same as the product of p by $\mathrm{A}x$.

As an illustration of the different courses by which a transition may be effected, suppose a quantity of gas initially at 0° C. and a pressure of one atmosphere, and finally at 100° C. and the same pressure, the final volume being therefore 1·366 times the initial volume. Of the innumerable courses by which the transition may be made, we will specify two:—

1st. The gas may be raised, at its initial volume, to such a temperature that, when afterwards allowed to expand against pressure gradually diminishing to one atmosphere, it falls to the temperature 100° C. Or,

2d. It may be first allowed to expand, under pressure diminishing from one atmosphere downwards, until its final volume is attained, and may then, at this constant volume, be heated up to 100°.

In both cases it is to be understood that no heat is allowed to enter or escape during expansion.

Obviously, the first course implies the performance of a greater amount of external work than the second, and it will require the communication to the gas of a greater quantity of heat,—greater by the heat-equivalent of the difference of works.

When a body passes through changes which end by leaving it in precisely the same condition in which it was at first, we are not entitled to assume that the amounts of heat which have entered and quitted it are equal. They are not equal unless the algebraic sum of external work done by the body during the changes amounts to zero. If the body has upon the whole done positive work, it must have taken in more heat than it has given out, otherwise there would be a creation of energy; and if it has upon the whole done negative work, it must have given out more heat than it has taken in, otherwise there would be a destruction of energy. In either case, *the difference between the heat taken in and given out must be the equivalent of the algebraic sum of external work.*

These principles are illustrated in the two following sections.

358 E. Lowering of Freezing-point by Pressure.—When a litre (or cubic decimetre) of water is frozen under atmospheric pressure, it forms 1·087 of a litre of ice, thus performing external work amounting to $\cdot 087 \times 103{\cdot}3 = 9$ kilogramme-decimetres = ·9 of a kilogrammetre, since the pressure of one atmosphere or 760 mm. of mercury is 103·3 kilogrammes per square decimetre. Under a pressure of n atmospheres, the work done would be $\cdot 9\,n$ kilogrammetres, neglecting the very slight compression due to the increase of pressure. If the ice is allowed to melt in vacuo, no external work is done upon it in the melting, and therefore, in the whole process, at the end of which the water is in the same state as at the beginning, heat to the amount of $\frac{\cdot 9n}{424} = \cdot 00212\,n$ of a calorie is made to disappear. This process is *reversible*, for the water might be frozen in vacuo and melted under pressure; and hence, by appendix (2) to the second law of thermo-dynamics, we have

$$\cdot 00212\,n \;:\; \mathrm{Q} \;::\; \mathrm{T} - \mathrm{T}' \;:\; \mathrm{T};$$

where Q denotes the heat taken in in melting, which is 79·25 calories, T the absolute temperature at which the melting occurs, about 273°, and T′ the absolute temperature of freezing under the pressure of n atmospheres. Hence we have

$$\cdot 00212\,n \;:\; 79{\cdot}25 \;::\; \mathrm{T} - \mathrm{T}' \;:\; 273;$$

$$\mathrm{T} - \mathrm{T}' = \cdot 0073\,n;$$

that is, the freezing-point is lowered by ·0073 of a degree Cent. for each atmosphere of pressure.

358F. Latent Heat at Temperatures below the Melting-point.—We have seen (§ 231) that water may be preserved in the liquid state at temperatures considerably below its normal freezing-point. When ice is formed at these low temperatures, the latent heat absorbed must be less than 79·25, which is the latent heat at 0° C. For, neglecting the trifling amount of external work performed, we can assert that the heat lost from a mass of water at 0°, in its passage to ice at $-t°$, is independent of the order of operations. Now the specific heat of ice is ·504, that of water being 1; hence the heat lost in making the transition in the ordinary way is $79·25 + ·504\,t$, while that lost by first cooling down, and then freezing at $-t°$ is $l+t$, l denoting the latent heat at $-t°$. Equating these two expressions, we have $l=79·25-·496\,t$.

We have here assumed that the specific heat of ice is ·504 at all temperatures. Person's experiments seem to show that within a degree or two of the melting-point it has a much larger value.

If the specific heats both of ice and water were constant at all temperatures, we might determine the position of the absolute zero of temperature by putting $l=0$, which gives $-t°=-160°$ nearly, a result which differs widely from that deduced from the laws of gaseous expansion.

Allowing for possible variations of specific heat with temperature, the expressions for the heat evolved in passing from water at 0° to ice at $-t°$ are $79·25+ts'$ and $l+ts$, in which s denotes the mean specific heat of water between 0° and $-t°$, and s' the mean specific heat of ice between the same limits. Equating these two expressions, we find

$$l=79·25-t(s-s').$$

When freezing once begins at a temperature below 0°, it proceeds very rapidly, accompanied by a rise of temperature, and ceases as soon as the temperature of the whole mass has risen to 0°. To compute the proportions of ice at 0° and water at 0° which a given mass of water at $-t°$ will yield, we may reason as follows:—Calling the whole mass unity, to raise it from its initial condition to 0°, and then convert a fraction m of it into ice at 0°, would require first the addition of t heat-units, and then the subtraction of $79·25\,m$ heat-units, that is upon the whole an addition of $t-79·25\,m$. Now the external work being inconsiderable, the amount of heat required from without for the conversion of a mass 1 of water at $-t^\circ$ into m of ice at 0° and $1-m$ of water at 0°, will be independent of the order of procedure; and in the given case no heat is added from without; we have therefore

$$t - 79{\cdot}25\,m = 0, \quad m = \frac{t}{79{\cdot}25}.$$

359. Animal Heat and Work.—We have every reason to believe that animal heat and motions are derived from the energy of chemical combinations, which take place chiefly in the act of respiration, the most important being the combination of the oxygen of the air with carbon which is furnished to the blood by the animal's food. The first enunciation of this view has been ascribed to Lavoisier. Rumford certainly entertained very clear and correct ideas on the subject, for he says, in describing his experiments on the boring of cannon:—

"Heat may thus be produced merely by the strength of a horse, and, in a case of necessity, this heat might be used in cooking victuals. But no circumstances could be imagined in which this method of procuring heat would be advantageous; for more heat might be obtained by using the fodder necessary for the support of a horse as fuel."

When the animal is at rest, the heat generated by chemical combination is equal to that given off from its body; but when it works, an amount of heat disappears equivalent to the mechanical effect produced. This may at first sight appear strange, in view of the fact that a man becomes warmer when he works. The reconciliation of the apparent contradiction is to be found in the circumstance that, in doing work, respiration is quickened, and a greater quantity of carbon consumed.

Elaborate experiments on this subject were conducted by Hirn. He inclosed a man in a box containing a tread-mill, the shaft of which passed through the side of the box; and the arrangements were such that the man could either drive the mill against external resistance, by continually stepping from one tread to the next above in the usual way, or could resist the motion of the mill when driven from without, by continually descending the treads, thus doing negative work. Two flexible tubes were connected, one with his nostrils, and the other with his mouth. He inhaled through the former, and exhaled th[illegible] the latter, and the air exhaled was collected and analyzed. T[illegible]n off from his body to the box was also measured with [illegible]proximation. The carbon exhaled, and heat generated, were both tolerably constant in amount when the man was at rest. When he was driving the mill by ascending the treads, the heat given out was increased, but the carbon exhaled was increased in a much greater ratio. When he was doing negative work by descending the treads, the heat given out, though less in absolute amount, was greater in proportion to the carbon exhaled, than in either of the other cases.

360. Heat of Chemical Combination.—There is potential energy between the particles of two substances which would combine chemically if the opportunity were afforded. When *combination* actually takes place, this potential energy runs down and yields an equivalent of heat. We may suppose that the particles rush together in virtue of their mutual attraction, and thus acquire motions which constitute heat.

In every case of *decomposition*, an amount either of heat or some other form of energy must be consumed equivalent to the heat of combination.

360A. Vegetable Growth.—In the growth of plants, the forces of chemical affinity do negative work. Particles which were previously held together by these forces are separated, and potential energy is thus obtained. When wood is burned, this potential energy is converted into heat.

We are not, however, to suppose that plants, any more than animals, have the power of *creating* energy. The forces which are peculiar to living plants are merely *directive*. They direct the energy of the solar rays to spend itself in separating the carbon and oxygen which exist united in the carbonic acid of the air; the carbon being taken up by the plant, and the oxygen left.

Coal is the remnant of vegetation which once existed on the earth. Thus all the substances which we are in the habit of employing as fuel, are indebted to the sun for the energy which they give out as heat in their combustion.

361. Solar Heat.—The amount of heat radiated from the sun is great almost beyond belief. The best measures of it have been obtained by two instruments which are alike in principle—Sir John Herschel's *actinometer* and Pouillet's *pyrheliometer*. We shall describe the latter, which is represented in Fig. 314. At the upper end, next the sun, is a shallow cylinder composed of very thin copper or silver, filled with water in which the bulb of a thermometer is inserted, the stem being partially inclosed in the hollow tube which supports the cylinder. At the lower end of the tube is a disc equal and parallel to the base of the cylinder. This is intended to receive the shadow of the cylinder, and thus assist the operator in pointing the instrument directly towards the sun. The cylinder is blackened, in order that its absorbing power may be as great as possible.

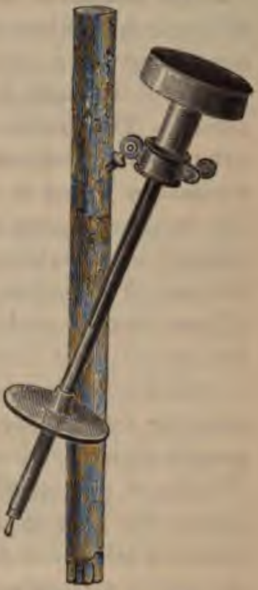


Fig. 314.—Pyrheliometer.

The instrument, initially at the temperature of the atmosphere, is first placed for five minutes in a position where it is exposed to the sky, but shaded from the sun, and the increase or diminution of its temperature is observed; suppose it to be a fall of θ°. The screen which shaded it from the sun is then withdrawn, and its rise of temperature is observed for five minutes with the sun shining upon it; call this rise T°. Finally, it is again screened from the sun, and its fall in five minutes is noted;—call this θ'°. From these observations it is inferred, that the instrument, while exposed to the sun, lost $\frac{\theta+\theta'}{2}$ to the air and surrounding objects, and that the whole heat which it received from the sun was $T+\frac{\theta+\theta'}{2}$, or rather was the product of this difference of temperature by the thermal capacity of the cylinder and its contents. This is the heat which actually reaches the instrument from the sun, but a large additional amount has been intercepted by absorption in the atmosphere. The amount of this absorption can be roughly determined by comparing observations taken when the sun has different altitudes, and when the distance traversed in the air is accordingly different. Including the amount thus absorbed, Pouillet computes that *the heat sent yearly by the sun to the earth would be sufficient to melt a layer of ice* 30 *metres thick, spread over the surface of the earth;* and Sir John Herschel's estimate is not very different.

The earth occupies only a very small extent in space as viewed from the sun; and if we take into account the radiation in all directions, the whole amount of heat emitted by the sun will be found to be about 2100 million times that received by the earth, or sufficient to melt a thickness of two-fifths of a mile of ice per hour over the whole surface of the sun.

361 A. Sources of Solar Heat.—The only causes that appear at all adequate to produce such an enormous effect, are the energy of the celestial motions, and the potential energy of solar gravitation. The motion of the earth in its orbit is at the rate of about 96,500 feet per second. The kinetic energy of a pound of matter moving with this velocity is equivalent to about 104,000 pound-degrees Centigrade, whereas a pound of carbon produces by its combustion only 8080. The inferior planets travel with greater velocity, the square of the velocity being inversely as the distance from the sun's centre; and the energy of motion is proportional to the square of velocity. It follows that a pound of matter revolving in an orbit just outside the sun would have kinetic energy about 220 times greater than if it travelled with the earth. If this motion were arrested by the body plunging into the sun, the heat generated would be about 2800 times greater than that given out by the combustion of a pound of charcoal. We know that small bodies are travelling about in the celestial spaces; for they often become visible to us as meteors, their incandescence being due to the heat generated by their friction against the earth's atmosphere; and there is reason to believe that bodies of this kind compose the immense circumsolar nebula called the zodiacal light, and also, possibly, the solar corona which becomes visible in total eclipses. It is probable that these small bodies, being retarded by the resistance of an ethereal medium, which is too rare to interfere sensibly with the motion of such large bodies as the planets, are gradually sucked into the sun, and thus furnish some contribution towards the maintenance of solar heat. But the perturbations of the inferior planets and comets furnish an approximate indication of the quantity of matter circulating within the orbit of Mercury, and this quantity is found to be such that the heat which it could produce would only be equivalent to a few centuries of solar radiation.

Helmholtz has suggested that the smallness of the sun's density—only $\frac{1}{4}$ of that of the earth—may be due to the expanded condition consequent on the possession of a very high temperature, and that this high temperature may be kept up by a gradual contraction. Contraction involves approach towards the sun's centre, and therefore the performance of work by solar gravitation. By assuming that the work thus done yields an equivalent of heat, he brings out the result that, if the sun were of uniform density throughout, the heat developed by a contraction amounting to only one ten-thousandth of the solar diameter, would be as much as is emitted by the sun in 2100 years.

361 B. Sources of Energy available to Man.—Man cannot produce energy; he can only apply to his purposes the stores of energy which he finds ready to his hand. With some unimportant exceptions, these can all be traced to three sources:—

I. The solar rays.

II. The energy of the earth's rotation.

III. The energy of the relative motions of the moon, earth, and sun, combined with the potential energy of their mutual gravitation.

The fires which drive our steam-engines owe their energy, as we have seen, to the solar rays. The animals which work for us derive their energy from the food which they eat, and thus, indirectly, from the solar rays. Our water-mills are driven by the descent of water, which has fallen as rain from the clouds, to which it was raised in the form of vapour by means of heat derived from the solar rays.

The wind which propels our sailing-vessels, and turns our windmills, is due to the joint action of heat derived from the sun, and the earth's rotation.

The tides, which are sometimes employed for driving mills, are due to sources II. and III. combined.

The work which man obtains, by his own appliances, from the winds and tides, is altogether insignificant when compared with the work done by these agents without his intervention, this work being chiefly spent in friction. It is certain that all the work which they do, involves the loss of so much energy from the original sources; a loss which is astronomically insignificant for such a period as a century, but may produce, and probably has produced, very sensible effects in long ages. In the case of tidal friction, great part of the loss must fall upon the energy of the earth's rotation; but the case is very different with winds. Neglecting the comparatively insignificant effect of aerial tides, due to the gravitation of the moon and sun, wind-friction cannot in the slightest degree affect the rate of the earth's rotation, for it is impossible for any action exerted between parts of a system to alter the angular momentum of the system (53 F.) The effect of easterly winds in checking the earth's rotation must therefore be exactly balanced by the effect of westerly winds in accelerating it. In applying this principle, it is to be remembered that the couple exerted by the wind is jointly proportional to the force of friction resolved in an easterly or westerly direction, and to the distance from the earth's axis.

361c. Dissipation of Energy.—From the principles laid down in the present chapter it appears that, although mechanical work can be entirely spent in producing its equivalent of heat, heat cannot be entirely spent in producing mechanical work. Along with the conversion of heat into mechanical effect, there is always the transference of another and usually much larger quantity of heat from a body at a higher to another at a lower temperature. In conduction and radiation heat passes by a more direct process from a warmer to a colder body, usually without yielding any work at all. In these cases, though there is no loss of energy, there is a running to waste as far as regards convertibility; for a body must be hotter than neighbouring bodies, in order that its heat may be available for yielding work. This process of running down to less available forms has been variously styled *diffusion*, *degradation*, and *dissipation* of energy, and it is not by any means confined to heat. We can assert of energy in general that it often runs down from a higher to a lower grade (that is to a form less available for yielding work), and that, if a quantity of energy is ever raised from a lower to a higher grade, it is only in virtue of the degradation of another quantity, in such sort that there is never a gain, and is generally a loss, of available energy.

This general tendency in nature was first pointed out by Sir W. Thomson. It obviously leads to the conclusion that the earth is gradually approaching a condition in which it will no longer be habitable by man as at present constituted.

CHAPTER XXXIII.

STEAM AND OTHER HEAT ENGINES.

362. Heat-engines.—The name of heat-engine or thermo-dynamic engine is given to all machines which yield work in virtue of heat which is supplied to them. Besides the steam-engine, it includes the air-engine and the gas-engine. We shall first describe one of the best forms of the air-engine.

363. Stirling's Air-engine.—Fig. 315 is a perspective view, and Fig. 316 a section of the engine invented by Dr. Robert Stirling. The particular form here represented is that which has been adopted in France by M. Laubereau. It consists of two cylinders of different diameters, which are in communication with each other. The larger cylinder is divided into two compartments by a kind of large piston made of plaster of Paris, which, however, does not touch the sides of the cylinder, and thus leaves an annular space for communication between the two compartments.

The bottom of the large cylinder, which is directly exposed to the action of the furnace, is slightly concave; the top is double, thus affording an intermediate space, through which cold water is kept circulating by means of a pump which is driven by the machine. From this arrangement it follows that, when the mass of plaster is at the bottom of the cylinder, it will intercept the heat of the fire, being a very bad conductor, and thus the air in the cylinder will be cooled by the water in the double top. On the other hand, when the piston is in contact with the refrigerator, the air will be exposed to the action of the fire, and its elastic force will, consequently, be increased.

ove, and contains a piston which
wheel of cast-iron. The com-
n the lower part

Suppose now that the large piston is in contact with the refrigerator, while the small piston is in its lowest position. The air is thus exposed to the action of heat, expands, and raises the small piston. If we now suppose the large piston shifted to the bottom of the cylinder, the air will cool, and its tension will diminish, becoming equal to or even less than that of the atmosphere. The small piston will thus be carried to the bottom of the cylinder by the movement of the fly-wheel, and will again be pushed up by the expanding air, if we suppose the large piston to rise again to the top of its cylinder.

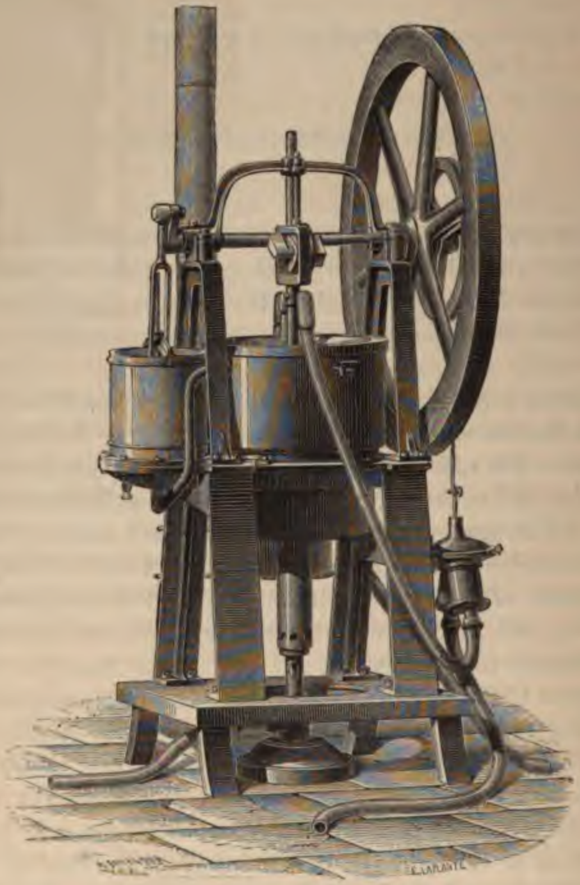


Fig. 315.—Stirling's Air-engine.

This motion of the large piston is effected, as shown in the figure, by means of an eccentric on the axle of the fly-wheel. The engine is of small size, and is intended for purposes requiring but little power. To obtain high efficiency, according to the principles of the preceding chapter, the difference of temperature between the two ends of the large cylinder should be very great. This amounts to saying that the lower end must be kept very hot, since it is practically impossible to keep the upper end much cooler than the surrounding atmosphere. The facility of maintaining a very high temperature constitutes at once the strength and the weakness of the air-engine. The bottom of the cylinder becomes rapidly oxidized, and needs frequent renewal. Partly for this reason, and partly on account of the small expansibility of air as compared with the expansion which takes place when water is converted into steam, air-engines are seldom employed for high powers.

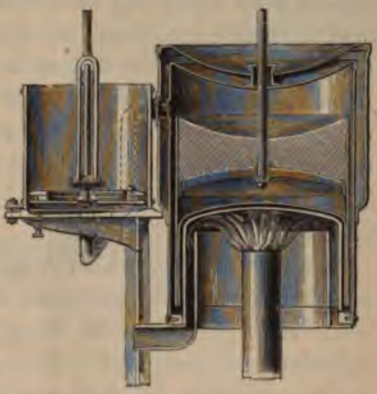


Fig. 316.—Section of Stirling's Air-engine.

364. The Steam-engine: its History.—As early as the seventeenth century, when Otto Guericke and Torricelli were investigating the pressure and the weight of air, attention had been given to the physical properties of steam, and the idea of employing it as a source of work had been entertained.

The first person who made steam drive a piston was Papin, a French philosopher, inventor of the digester and the safety-valve (born 1650; died 1710). About the year 1690 he constructed a working model, consisting of a cylinder open at the top, containing a piston and a little water below it. The water was converted into steam by the application of heat, and raised the piston. The machine being then allowed to cool, the steam lost its tension, and the pressure of the atmosphere forced the piston to descend. A backward and forward motion was thus obtained, which Papin proposed to convert into a rotatory motion by means of rack[1] and pinion work and ratchet-wheels.

---

[1] A rack is a straight bar wit [illegible] e, which works with a toothed wheel called a pinion

A description of Papin's machine is given in the *Acta Eruditorum* under date 1690.

The first steam-engine actually employed for doing useful work was invented by Savery about 1697, and was extensively used for draining mines. Steam from a separate boiler was admitted to press upon the surface of water in a vessel, and thus force it up through an ascending pipe; and on the condensation of the steam, water from a lower level was raised into the vessel by atmospheric pressure. The condensation was effected by applying cold water to the outside of the vessel.

Savery's engine, which was a steam-pump, and not an engine adapted for general purposes, was superseded by an engine jointly contrived by Newcomen, Savery, and Cawley, which combined the cylinder and piston with the separate boiler and with condensation by the injection of cold water into the cylinder. This engine is generally referred to as Newcomen's atmospheric engine,—so called because the descent of the piston was produced by atmospheric pressure, on the condensation of the steam beneath it.

James Watt (born 1736; died 1819), who effected the most important improvements in the steam-engine, had his attention called to the subject when engaged in repairing a model of Newcomen's engine, being at that time philosophical instrument maker to the University of Glasgow. His first improvement consisted in the introduction of a separate vessel for the condensation of the steam, so as to allow of keeping the cylinder always hot.

This first improvement, which immediately produced a great saving of fuel, was followed by another of scarcely less importance. This consisted in substituting the pressure of steam for the atmospheric pressure, which in Newcomen's engine caused the downward stroke of the piston. The upward stroke was effected by means of a counterpoise, the steam being admitted to press equally both above and below the piston. These two improvements, and a general perfecting of the details of the machinery, caused Watt's engine to supersede that of Newcomen. The engine thus contrived by Watt is called *single-acting*, because only the down-stroke of the piston is produced by the pressure of steam. This arrangement is particularly adapted for pumping, and is commonly employed at the present day for draining mines. It was not long before Watt perfected his engine by employing steam to produce both the up-stroke and the down-stroke. This is the characteristic of the *double-acting* engine, which was carried to a high degree of perfection by the inventor himself, and which is now most frequently adopted as the source of moving power. We may add that the improvements introduced in the steam-engine since Watt's time have been matters of detail rather than of principle. We proceed to describe Watt's engine.

365. Principle of the Double-acting Engine.—M (Fig. 317) is a boiler communicating with the top and bottom of the cylinder by means of two stop-cocks *a* and *b*. Connection can be established between the cylinder and the condenser I by two other cocks *c* and *d*. If now the cocks *a* and *c* are opened, and *b* and *d* shut, the steam from the boiler will arrive above the piston P, while that which was previously introduced below will, by communication with the condenser, be more or less condensed, and will thus lose its elastic force; the piston will accordingly descend to the bottom of the cylinder. The two cocks *b* and *d* are then opened, while the other two are shut; the steam above the piston is thus condensed, while that below the piston forces it up, thus causing the upward stroke, after which the piston may again be made to descend, and so on.

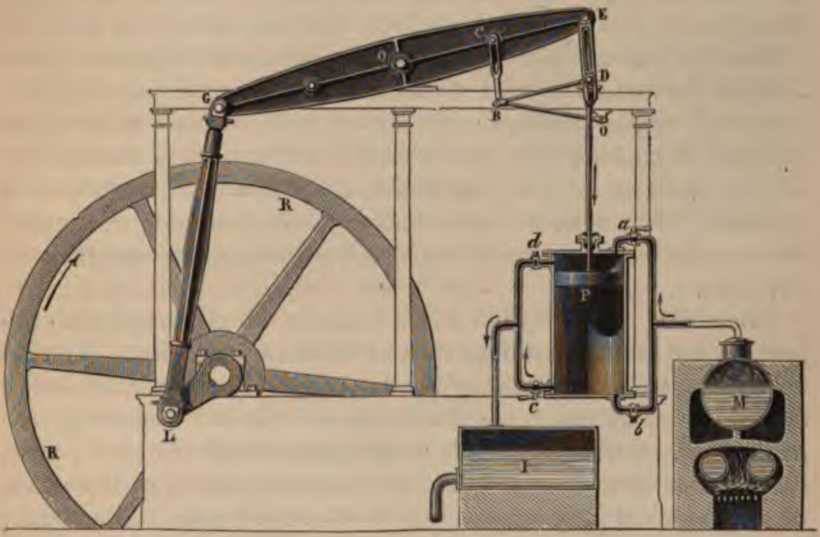


Fig. 317.—Principle of the Double-acting Engine.

We thus see that, by suitable manipulation of the stop-cocks [illegible] we can give the piston a backward and forward motion, which [illegible] transformed into one of r[illegible] For this purpose the piston-rod is connected with one end of the beam EG by the jointed parallelogram CBDE, while the other end of the beam is jointed to the connecting-rod GL, which is itself jointed to the crank of the fly-wheel RR.

It will be seen that, if the piston descends, the action of the crank will drive the wheel in the direction shown by the arrow. When the piston has completed its downward stroke, the connecting-rod and the crank will be in a straight line, and the action of the former upon the latter will have no tendency to turn the wheel either way. This position is called a *dead point.* But the momentum acquired by the fly-wheel will carry it past this position, and, the piston having then commenced its upward stroke, the rotatory movement will continue in the same direction until the rod and crank are at the other *dead point,* which occurs at 180° from the first, and is passed over in the same way. We thus see that, by means of the alternate motion of the piston, we can obtain a rotatory motion, which may be imparted to a horizontal shaft, and made to drive machinery of any kind.

The jointed parallelogram which connects the piston-rod with the beam is one of the most ingenious of the improvements introduced by Watt. Its use is evident. When the engine is at work, the end E of the beam describes an arc of a circle, while the end D of the piston-rod moves in a straight line; it is therefore impossible to joint them directly together. They are therefore connected through the medium of the short rod ED, which, with the two other rods, BD and BC, together with the part CE of the beam, form a *jointed parallelogram,* the angles of which can vary according to the position of the beam. The angle B is connected by a joint with the end of the *radius-rod* BO, movable about the fixed point O. The effect of this arrangement is as follows:—If we take the beam in a horizontal position, and suppose the end E to rise, the point D will be drawn towards the left by the action of the beam, and towards the right by the action of the radius-rod BO, which, from its checking the movement of the piston-rod to either side, is often called the *bridle-rod.* It will easily be understood that these two contrary actions may be made to balance each other almost exactly, and that, accordingly, the path of D will deviate very little from a straight line.

366. Arrangement for Admitting the Steam.—We have simplified the description of the steam-engine by supposing that the cocks *a* and *c*, *b* and *d* were alternately opened by hand. This, however, is not the actual arrangement, the opening and closing of the passages being really effected by automatic movements. The most usual arrangement for this purpose is the *slide-valve*, which we now proceed to describe.

The steam, instead of entering the cylinder directly, passes into it from a box in front of it (Fig. 318), which is called the *valve-chest.* In the opposite face of the box from that at which the steam enters, are three holes or *ports* near each other. The uppermost of these communicates with the upper part of the cylinder; the lowest one with the lower part; and the middle hole with *o*, which itself is in communication with the condenser. Upon this face of the box there slides a rectangular piece of metal, hollowed out on the side next these openings, and large enough to reach over two of the ports at once.

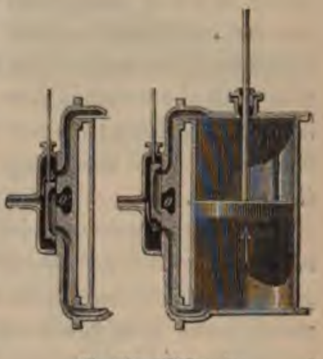


Fig. 318.—Slide-valve.

In the right-hand figure this *slide-valve* is supposed to be at the top of its upward stroke, thus admitting the steam below the piston, and pushing it in the direction indicated by the arrow; while the steam above the piston is put in communication with the condenser. In the left-hand figure, the opposite position is shown; the steam is admitted above the piston, while the lower part of the cylinder is in communication with the condenser.

367. Movement of the Sliding-valve.—It is desirable that the movement of the slide-valve should be automatic; for this purpose the following arrangement is employed. A circular piece of metal *e*, called the *eccentric*, is traversed by the shaft of the engine in a point which is not the centre of the piece, and is rigidly attached to the shaft. [illegible]ic is surrounded with a ring of metal, which can

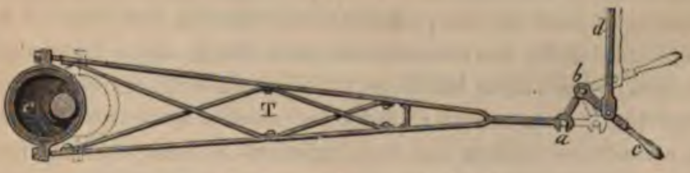


Fig. 319.—Eccentric for moving Slide-valve.

turn freely about it, and which forms part of the triangular frame T. The vertex of the triangle is fastened to a bent lever *abc*, which thus receives an oscillatory movement about the point *b*. This movement raises and lowers alternately the rod *d*, which is attached to the sliding-valve, and thus gives that valve its motion.

368. Air-pump of the Condenser.—The condenser is a cylinder into which a jet of cold water constantly plays, the quantity of which can be increased or diminished at pleasure. The steam, in its condensation, heats the cold water, and at the same time the air contained in the water is disengaged, owing to the small pressure in the condenser. It is thus found necessary to pump out both the air and the water; and the pump which does this is driven by the beam of the engine.

The warm water thus drawn out is conducted to a reservoir, whence a portion of it is raised by a second pump, and forced into the boiler. Finally, a third pump, usually of greater power than the other two, raises water from some external source, and discharges it into a bath called the *cold well*, which feeds the condenser. These last two pumps are also connected with the beam of the engine.

369. Governor-balls.—The apparatus called the governor-balls or the *centrifugal governor* was designed by Watt for the purpose of regulating the admission of steam in such a manner as to render the rate of the engine nearly constant through all variations of the resistance to be overcome.

It consists of a vertical axis *y* (Fig. 320), which receives a rotatory movement from the machine. To the top of this are jointed two rods $\alpha\beta$, $\alpha'\beta'$, carrying the heavy balls Z and Z′. Two other rods, $\beta\epsilon$, $\beta'\epsilon'$, are jointed to the first, so as to form with them a lozenge, the lower end of which is fastened to a sliding-ring *m*, which surrounds the axis of rotation. When the engine is at rest, the sides of the lozenge are as near as possible to the vertical, but when it begins to work, the balls are carried out from the vertical by centrifugal force, and the distance increases with the velocity of rotation. The sliding-ring is thus raised, and, by means of a system of levers, acts upon a throttle-valve (a disc turning about a diameter) in the steam-pipe, so as to diminish the supply of steam to the cylinder when the velocity increases.

370. Use of the Fly-wheel.—From the mode in which the motion of the piston is transmitted to the shaft, it is obvious that the driving couple undergoes great variations of magnitude. It is greatest (considered statically) when the crank is nearly at right angles to the connecting-rod, and diminishes in approaching the dead points, where it vanishes altogether. These variations in the driving couple tend to produce corresponding variations in the velocity of rotation.

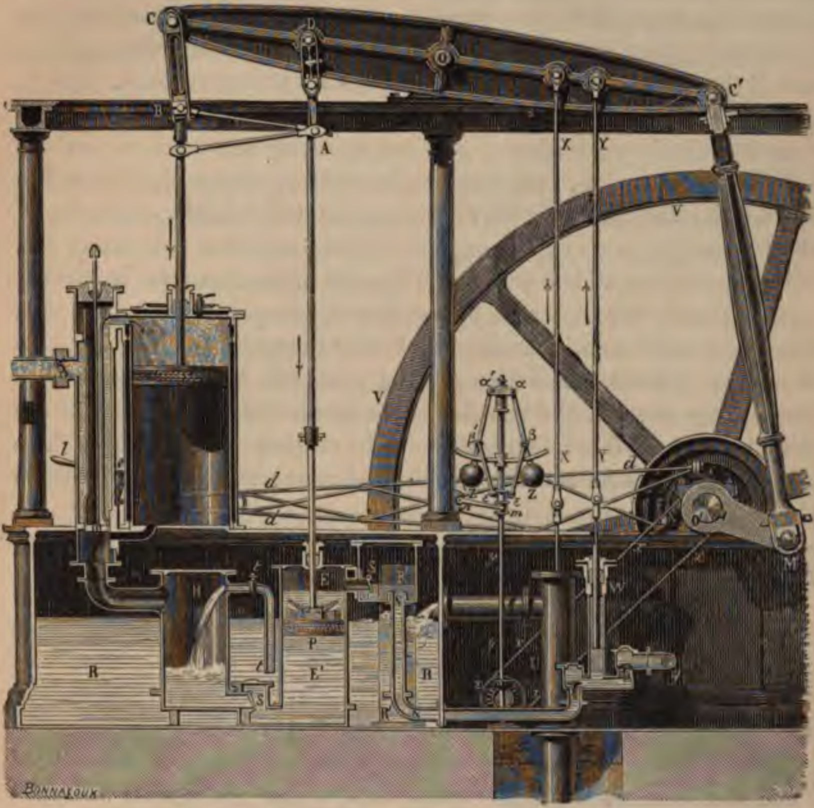


Fig. 320.—WATT'S ENGINE.

ABCD, jointed parallelogram. CC', beam, turning about O. C'M, connecting-rod. O'M, crank, attached to axis of fly-wheel. VV, fly-wheel. *c*, eccentric, which, by means of the frame *dd*, moves the lever *el*, which moves the slide-valve. *xx*, an endless cord, passing over a pulley on the axis O', and over a second pulley *z*, whose motion is transmitted by bevel-wheels to the axis *y* of the centrifugal governor. *am*, a rod moved by the ring *m*, and transmitting its movement by means of levers to the throttle-valve. H, condenser. RR, cold well. *t*, tube through which the water of the cold well under atmospheric pressure flows into the condenser. EE', cylinder of exhaust-pump. P, piston of ditto. S, valve. X, rod of the pump U which supplies the cold well. R', bath which receives the water drawn from the condenser. Y, rod of the feed-pump W, which draws water from R' and forces it into the boiler.

Other causes also [illegible] to produce the same result, especially the variations in [illegible] resistance to be overcome. If, for instance, the engine drives a wheel with cams which raise a tilt-hammer, when the hammer falls the principal resistance is removed, and the engine immediately begins to quicken its speed. When the hammer is caught again by the next cam, the velocity is suddenly diminished, and so on. Similar results, though not of so marked a character, are produced in engines of all kinds. These sudden changes of velocity, if not mitigated, would be very injurious to the mechanism of the engine, by the shocks which they would produce.

The use of the fly-wheel is to remedy this evil. It is a wheel of considerable size and weight (the weight being collected as much as possible at the rim), and receives a rotatory movement from the engine. If the driving power increases, or the resistance diminishes, all the moving parts of the engine acquire increased velocities; but the greatest part of the additional energy of motion thus generated goes to the fly-wheel, which has such a large moment of inertia that a very slight change in its angular velocity represents a large amount of energy (§ 53G). The energy thus absorbed by the fly-wheel is restored by it when the velocity is checked; and the rotation of the shaft is thus rendered nearly uniform in all parts of the stroke. The size of the fly-wheel is usually made such that the difference between the greatest and least velocities shall not exceed about $\frac{1}{30}$ of the mean velocity.

371. General Description of Watt's Engine.—The explanations above given will enable the reader to understand the general arrangement of Watt's engine as represented in Fig. 320. It is merely necessary to remark that the slide-valve is slightly different from that described above, but the modification is not of any importance.

372. Working Expansively.—Among the modifications introduced since Watt's time, we must notice in the first place what is called *expansive working*.[1] When the piston has performed a part of its stroke, the steam is shut off (or in technical phrase *cut off*) from the cylinder, and the expansive force of the steam already admitted is left to urge the piston through the remainder of its course. By this means a great economy of steam may be effected. The part of the stroke at which the cut-off occurs may be determined at pleasure. It is sometimes at half-stroke, sometimes at quarter-stroke, sometimes at one-fifth of stroke. In the latter case, the piston describes the remaining four-fifths of its stroke under the gradually diminishing pressure of the steam which entered the cylinder during the first fifth; and the work done during these four-fifths is so much work gained by working expansively.

---

[1] This was one of Watt's inventions, but it has been much more fully developed in recent times.

373. Modification of Slide-valve for Expansive Working.—The cutting-off of the steam before the end of the stroke is usually effected by the contrivance represented in Fig. 321: *a d*, *a′d′*, are two plates forming part of the slide-valve and of much greater width than the openings L, L′. The excess of width is called *lap*. By this arrangement one of the apertures is kept closed for some time, so that the steam is shut off, and acts only by its expansion. The expansion increases with the lap, but not in simple proportion, as equal movements of the slide-valve do not correspond to equal movements of the piston. The amount of expansion can also be regulated by means of the *link-motion*, which will be described in § 390.

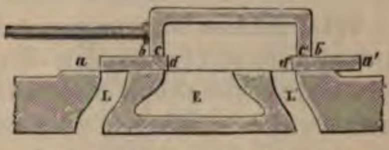


Fig. 321.—Slide-valve for Expansive Working.

374. Compound Engines.—This is the name given to engines in which the steam performs the greater part of its expansion in a second cylinder, of much larger cross-section than the first, the increased area of pressure on the piston serving to compensate for the diminished intensity of pressure which exists in the latter part of the stroke, and thus to produce greater steadiness of driving-power. Various methods have been adopted for connecting the two cylinders. One arrangement for this purpose is represented in Fig. 322. *p* is the smaller piston, working in the smaller cylinder ABCD. P is the larger piston, working in the larger cylinder A′B′C′D′. In the up-stroke, the passage DA′ is closed, and CB′ is open. The small piston is forced up by the high-pressure steam beneath, while the steam above it, instead of escaping to a condenser, expands into the large cylinder, and there raises the piston P, the upper part of the large cylinder being connected with the condenser. I [illegible] stroke, the passage CB′ is closed, and

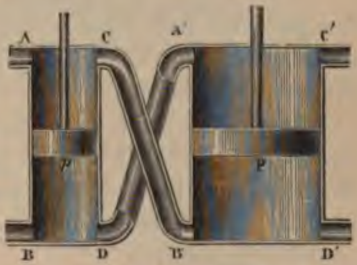


Fig. 322.—Compound-cylinder Arrangement.

D A′ is open. The two piston-rods are connected with the same end of the beam, and rise and fall together. The distribution of the steam is effected by means of two slide-valves, each governed by an eccentric.

Compound engines have been adopted for some lines of ocean-steamers, where it is of primary importance to obtain as much work as possible from a limited quantity of fuel. Engineers are, however, divided in opinion as to whether any advantage attends their use.

374A. Surface Condensation.—In several modern engines, the condenser consists of a number of vertical tubes of about half an inch diameter, connected at their ends, and kept cool by the external contact of cold water. The steam, on escaping from the cylinder, enters these tubes at their upper ends, and becomes condensed in its passage through them, thus yielding distilled water, which is pumped back to feed the boiler. The same water can thus be put through the engine many times in succession, and the waste which occurs is usually repaired by adding from time to time a little distilled water prepared by a separate apparatus.

375. Classification of Steam-engines.—The distinctions which exist between different kinds of stationary engines relate either to the pressure of the steam, or to its mode of action, or to the arrangement of the mechanism, especially as regards the mode in which the movement of the piston is transmitted to the rest of the machinery.

On the first of these heads, it must be remarked that the terms *low-pressure* and *high-pressure* are no longer equivalent to *condensing* and *non-condensing* as they once were, and merely express differences of degree.

When the pressures employed are very low there is little risk of explosion and little wear and tear; but the engine must be very large in proportion to its power, and expansive working cannot be employed. Low-pressure engines are always *condensing*, though the converse is not true.

With regard to the mode of action of the steam, engines may be classed as condensing or non-condensing, as expansive or non-expansive. Condensation increases the quantity of work obtainable from a given consumption of fuel, and is almost always employed for stationary engines where the supply of water is abundant, and also for marine engines, but it is dispensed with in locomotives and agricultural engines.

Expansive working is also conducive to efficiency, as is obvious from § 372. Assuming the temperature of the steam to remain constant during the expansion, the following table, calculated by an application of Boyle's law, exhibits the relative amounts of work

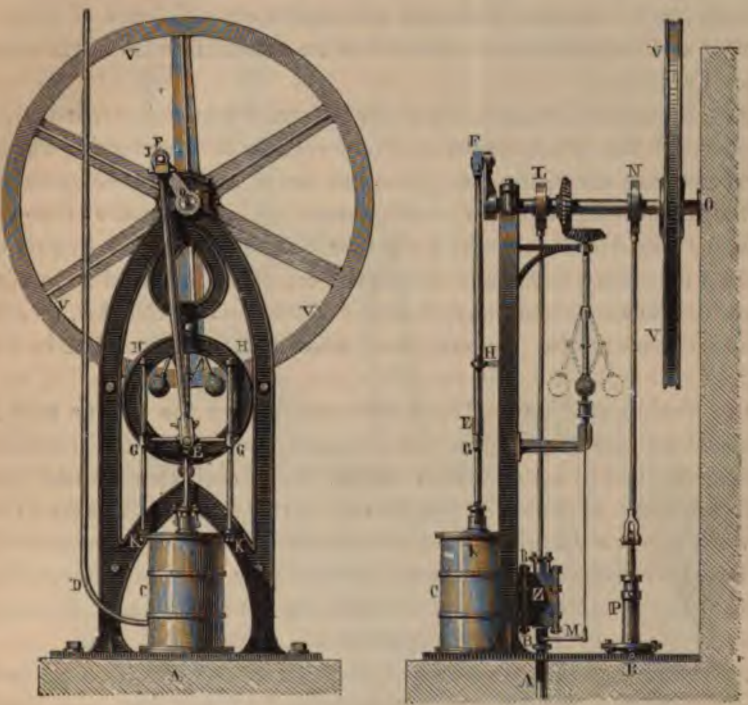


Fig. 323.—High-pressure Engine with Vertical Cylinder, working Expansively and without Condensation.

A, steam-pipe through which the steam arrives from the boiler. Z, valve-chest. B, slide-valve. C, cylinder. G G, guides fixed to the cylinder and to the frame of the engine at K and H. E F, connecting-rod. J, crank. V V, fly-wheel. L, eccentric governing the slide-valve. N, eccentric of the exhaust-pump P. D, outlet pipe for the steam. M, lever of throttle-valve, regulated by centrifugal governor.

obtained from the same weight of steam with different ranges of expansion:—

Fraction of the stroke completed before the shutting-off of steam.	Work done.	Fraction of the stroke completed before the shutting-off of steam.	Work done.
1·0	1·000	·5	1·693
·9	1·105	·4	1·916
·8	1·223	·3	2·201
7	1·357	·2	2·609
[illegible]	1·509	·1	3·302

Expansive working is often combined with the *superheating* of steam, that is to say, heating the steam after it has been formed, so as to raise its temperature above the point of saturation. This increases the difference of temperatures to which, according to the second law of thermo-dynamics, the maximum efficiency is proportional; and experience has shown that an actual increase of efficiency is thus obtained.

376. Form and Arrangement of the Several Parts.—As regards their mechanism, the arrangement of steam-engines is considerably varied. In stationary condensing engines, the beam and parallelogram are usually retained; but the arrangement of high-pressure non-condensing engines is generally simpler. The piston-rod frequently travels between guides, and drives the crank by means of a connecting-rod. The cylinder may be either vertical or horizontal, or even inclined at an angle. An engine of this kind is represented in Fig. 323.

Oscillating Engines.—The space occupied by the engine may be lessened by jointing the piston-rod directly to the crank without any connecting-rod. In this case the cylinder oscillates around two gudgeons, one of which serves to admit the steam, the other to let it escape. The distribution of the steam is effected by means of a slide-valve whose movements are governed by those of the cylinder. Oscillating engines are very common in steam-boats, and usually produce an exceedingly smooth motion.

377. Rotatory Engines.—Numerous attempts have been made to dispense with the reciprocating movement of a piston, and obtain rotation by the direct action of steam. Watt himself devised an engine on this plan in 1782. Hitherto, however, the results obtained by this method have not been encouraging. Behren's engine, which we now proceed to describe, is one of the most promising of the rotatory engines.

Fig. 325 is a perspective view of the engine, and Fig. 326 a cross-section of the cylinders, showing the mode of action of the steam. C and C′ are two parallel axes, connected outside by two toothed wheels, so that they always turn in opposite directions. One of these axes is the driving-shaft of the engine. These two axes are surrounded by fixed collars *c* and *c*′, which fit closely to the cylindrical sectors E and E′; these latter, which are rigidly connected with the axes C, C′, are capable of moving in the incomplete cylinders A and A′, and act as revolving pistons. In the position represented in the figure, the steam enters at B, and will escape at D; it is acting only upon the sector E, and pushes it in the direction indicated by the arrow; the shaft C is thus turned, and causes the shaft C′ to turn in the opposite direction, carrying with it E′, to which it is attached. After half a revolution the sector E′ will be in a position corresponding, left for right, to that which E now occupies; it will then be urged by the steam, so as to continue the motion in the same direc-

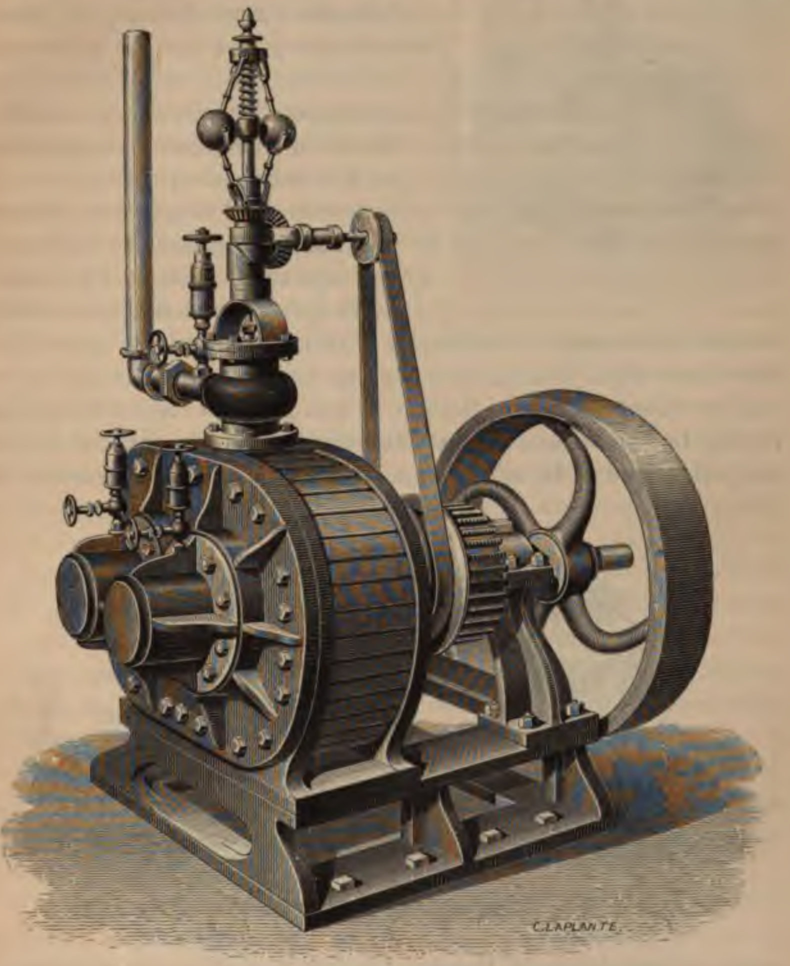


Fig. 325.—Behren's Rotatory Engine.

tion for another half-revolution, when the two sectors will have resumed the position represented in the figure.

380. Boilers.—There are many forms of boiler in use. That which is represented in Fig. 327 is the favourite form in France, and is also extensively used in this country, where it is called the *French boiler*, or the *cylindrical boiler with heaters*. The main boiler-shell A is cylindrical with hemispherical ends. BB are two cylindrical tubes called *heaters*, of the same length as the main shell, and connected with it by vertical tubes *d*, *d*, of which there are usually three to each heater. A horizontal brick partition, a little higher than the centres of the heaters, extends along their whole length; and a vertical partition runs along the top of each heater, except where interrupted by the vertical tubes. The flame from the furnace is thus compelled to travel in the first instance backwards, beneath the heaters; then forwards, through the intermediate space between the heaters the vertical tubes and the main shell; and lastly, backwards, through the side passages CC, which lead to the chimney. By thus compelling the flame to travel for a long distance in contact with the boiler, the quantity of heat communicated to the water is increased.

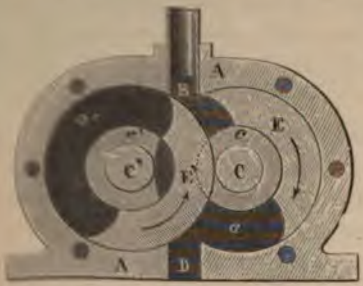


Fig. 326.—Section of Behren's Engine.

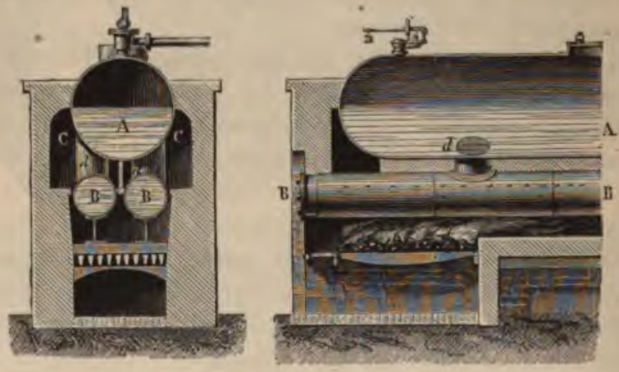


Fig. 327.—Boiler with Heaters.

The level of the water is shown at A in the left-hand figure. The relative spaces allotted to the steam and the water are not always the same; but must always be so regulated that the steam shall arrive in the cylinder as *dry* as possible, that is to say, that it shall not carry with it drops of water. Before being used, boilers should always be tested by subjecting them to much greater pressures than they will have to bear in actual use. Hydraulic pressure is commonly employed for this purpose, as it obviates the risk of explosion in case of the boiler giving way under the test.

381. Boilers with the Fire Inside.—When it is required to lessen the weight of the boiler, without much diminishing the surface exposed to heat, as in the case of marine engines, the method adopted is to place the furnace inside the boiler, so that it shall be completely surrounded with water except in front. The flame passes from the furnace, which is in the front of the boiler, into one or two large tubes, leading to a cavity near the back, whence it returns through a number of smaller tubes traversing the boiler, and finally escapes by the chimney.

382. Bursting of Boilers: Safety-valves.—Notwithstanding the tests to which boilers are subjected before being used, it too often happens that, owing either to excessive pressure or to weakening of the boiler, very disastrous explosions occur.

Excess of pressure is guarded against by gauges, which show what the pressure is at any moment, and by safety-valves, which allow steam to escape whenever the pressure exceeds a certain limit.

Various kinds of manometer or *pressure-gauge* have been described in Chap. xiv. That which is most commonly employed in connection with steam-boilers is Bourdon's (§ 126).

A thermometer, specially protected against the pressure and contact of the steam, is also sometimes employed, under the name of *thermo-manometer*, on the principle that the pressure of saturated steam depends only on its temperature.

The *safety-valve*, represented in the upper part of Fig. 327, consists of a piece of metal, having the form either of a truncated cone or of a flat plate, fitting very truly into or over an opening in the boiler. The valve is pressed down by a weighted lever; the weight and the length of the lever being calculated, so that the force with which the valve is held down shall be exactly equal to the force with which the steam would tend to raise it when at the limiting pressure. In movable engines, the weighted lever is replaced by a spring, the tens[illegible]h can be regulated by means of a screw.

Safety-valves afford ample protection against the danger arising from gradual increase of pressure; but they are liable to fail in cases where there is a sudden generation of a large quantity of steam. This explosive generation of steam may occur from various causes.

If, for instance, the water in the boiler is allowed to fall too low, the sides of the boiler may be heated to so high a temperature that, when fresh water is admitted, it will be immediately converted into steam on coming in contact with the metal.

Hence it is of great importance to provide that the water in the boiler shall not fall below a certain level, depending on the shape of the boiler and furnace.

The following are the means employed for securing this end:—

1. Two cocks are placed, one a little below the level at which the water should stand, and the other a little above it; these are opened from time to time, when water should issue from the first, and steam from the second.

2. The *water-gauge* is a strong vertical glass tube, having its ends fitted into two short tubes of metal, proceeding one from the steam-space and the other from the water-space. The level of the water is therefore the same in the gauge as in the boiler, and is constantly visible to the attendant. The metal tubes are furnished with cocks, which can be closed if the glass tube is accidentally broken.

384. Causes of Explosion.—Another cause of the explosive generation of steam is the incrustation of the boiler with a hard deposit, due to the impurities of the water employed. This crust is a bad conductor, and allows the portion of the boiler covered with it to become overheated; when, if water should find its way past the crust, and come in contact with the hot metal, there is great danger of explosion.

The best preventive of incrustation is the employment of distilled water in connection with surface condensation (§ 374A). In default of this, portions of the water in the boiler must be blown off from time to time so as to prevent it from becoming too highly concentrated. This is especially necessary when the boiler is fed with salt water.

Among the causes of the bursting of boilers, we may also notice undue smallness of the vertical tubes in boilers with heaters (§ 380). When this fault exists, the steam which is generated is not immediately replaced by water, and overheating is liable to occur.

Another cause of explosions is probably to be found in a property of water which has only recently been recognized. It has been shown that, when water is deprived of air, it does not begin boiling till it has acquired an abnormally high temperature, and then bursts into steam with explosive violence (§ 263, Donny's experiment). This danger is to be apprehended when a boiler, which has been allowed to cool after being for some time in use, is again brought into action without the addition of a fresh supply of water.

But it appears that the most frequent cause of boiler explosions is the gradual eating away of some portion of the boiler by rust, so as to render it at last too weak to withstand the pressure of the steam within it. The only general remedy for this danger is periodical and enforced inspection.

385. Feeding of the Boiler: Giffard's Injector.—The feeding of the boiler is usually effected by means of a pump driven by the engine itself. Of late years this plan has been largely superseded by Giffard's invention of an apparatus by means of which the boiler is supplied with water by the direct action of its own steam.

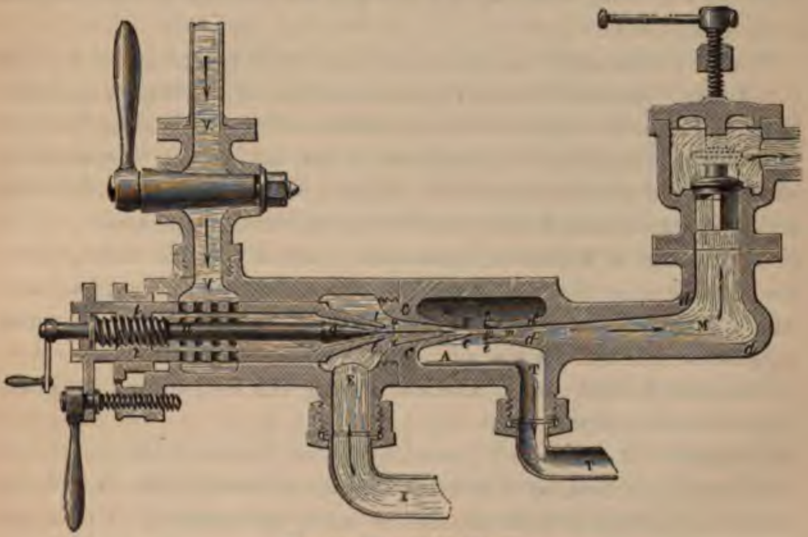


Fig. 328.—Giffard's Injector.

This very curious apparatus contains a conical tube *tt*, by which the steam issues when the injector is working; the steam from the boiler comes through the tube V V, and enters the tube *t t* through sm [illegible] its circumference. On issuing from the cone *t t*, the steam enters another cone *c c*, where it meets the water which is to feed the boiler, and which comes through the tube EE. The contact of the water and the steam produces two results: (1) the steam, which possesses a great velocity due to the pressure of the boiler, communicates part of its velocity to the water; (2) at the same time the steam is condensed by the low temperature of the water, so that at the extremity of the cone as far as *e e* the entire space is occupied by water only, with the exception of a few bubbles of steam which remain in the centre of the liquid vein.

The liquid, on issuing from the cone *c c*, traverses an open space for a little distance before entering the divergent opposite cone *d d*, through which it is conducted to the boiler by the pipe M. The water will not enter the boiler unless it possess a sufficient velocity to produce in the divergent cone a greater pressure than that which exists in the boiler; when this is the case, the excess of pressure opens a valve, and water enters the boiler from the injector.

We may complete this brief description by pointing out one or two arrangements by which the action of the apparatus is regulated. It is useful to be able to vary the volume of steam issuing through the cone *tt*, as required by the pressure in the boiler; this is easily effected by means of the pointed rod *a a*, which is called the *needle*, and is screwed forwards or backwards by turning a handle. It is also necessary to be able to regulate the volume of water which enters the cone *c c* from the supply-pipe E; this is done by means of a lever, which is not shown in the figure, and which moves the tube and cone *t t* forwards or backwards.

The tube E dips into a bath containing the feed-water; and AT is the overflow pipe.

It appears at first sight paradoxical that steam should be able, as in Giffard's injector, to overcome its own pressure, and force water into the boiler against itself; but it must be remembered that the water which is forced in is less bulky than the steam which issues, so that the exchange, though it produces an increase of mass in the contents of the boiler, involves a diminution of pressure, as well as a fall of temperature.

386. Locomotive: History.—The following sketch of the history of the locomotive is given by Professor Rankine.[1] "The application of the steam-engine to locomotion on land was, according to Watt, suggested by Robison in 1759. In 1784 Watt patented a locomotive-engine, which, however, he never executed. About the same time Murdoch, assistant to Watt, made a very efficient working model of a locomotive-engine. In 1802 Trevithick and Vivian patented a locomotive-engine, which was constructed and set to work in 1804 or 1805. It travelled at about 5 miles an hour, with a net load of ten tons. The use of fixed steam-engines to drag trains on railways by ropes, was introduced by Cook in 1808.

---

[1] *Manual of the Steam-engine*, pp. xxv–xxvii, edition 1866.

"After various inventors had long exerted their ingenuity in vain to give the locomotive-engine a firm hold of the track by means of rackwork-rails and toothed driving-wheels, legs and feet, and other contrivances, Blackett and Hedley, in 1813, made the important discovery that no such aids are required, the adhesion between smooth wheels and smooth rails being sufficient. To adapt the locomotive-engine to the great and widely-varied speeds at which it now has to travel, and the varied loads which it now has to draw, two things are essential—that the rate of combustion of the fuel, the original source of the power of the engine, shall adjust itself to the work which the engine has to perform, and shall, when required, be capable of being increased to many times the rate at which fuel is burned in the furnace of a stationary engine of the same size; and that the surface through which heat is communicated from the burning fuel to the water shall be very large compared with the bulk of the boiler. The first of these objects is attained by the *blast-pipe*, invented and used by George Stephenson before 1825; the second by the tubular boiler, invented about 1829, simultaneously by Séguin in France and Booth in England, and by the latter suggested to Stephenson. On the 6th October, 1829, occurred that famous trial of locomotive-engines, when the prize offered by the directors of the Liverpool and Manchester Railway was gained by Stephenson's engine the 'Rocket,' the parent of the swift and powerful locomotives of the present day, in which the blast-pipe and tubular boiler are combined. Since that time the locomotive engine has been varied and improved in various details, and by various engineers. Its weight now ranges from five tons to fifty tons; its load from fifty to five hundred tons; its speed from ten miles to sixty miles an hour."

389. Description of a Locomotive.—A section of a locomotive is represented in Fig. 329. The boiler is cylindrical. Its forward end abut ce beneath the chimney, called the *smoke-box.* At its othe r opening, surrounded above and on the two sides by the boiler, and called the *fire-box*. The fuel is heaped up on the bars which form the bottom of the fire-box, and the cinders fall on the line. The fire-box and smoke-box are connected by brass tubes, firmly rivetted to the ends of the boiler; and the products of combustion escape by traversing these from end to end. The tubes are very numerous, usually from 150 to 180, thus affording a very large heating surface. The water in the boiler stands high enough to cover all the tubes, as well as the top of the fire-box. Its level is indicated in the same way as in stationary engines; and water is pumped in from the tender as required; its amount being regulated by means of a stop-cock in the pipe *e'*.

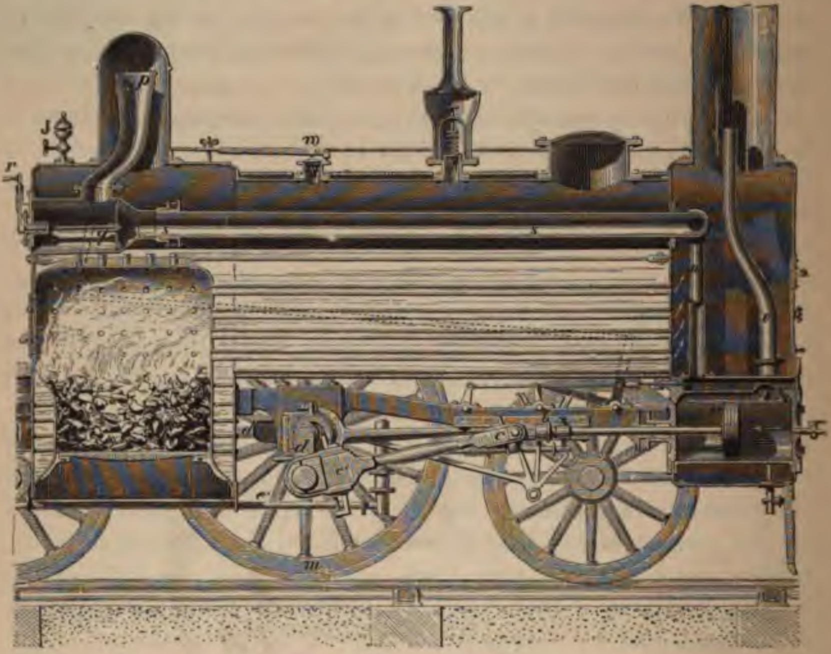


Fig. 329.—Section of Locomotive.

The steam escapes from the boiler by ascending into a dome, which forms its highest part, and thence descending the tube *p*, this arrangement being adopted in order to free the steam from drops of water. It then passes through a *regulator* *q*, which can be opened to a greater or less extent, into the pipe *s*, which leads to the valve-chests and traverses the whole length of the boiler. There are two cylinders, one on each side of the engine, each having a valve-chest and slide-valve, by means of which steam is admitted alternately before and behind the pistons. The steam escapes from the cylinder, through the blast-pipe *v*, up the chimney, and thus increases the draught of the fire. *a* is one of the pistons, *b* the piston-rod, *cc′* the connecting-rod, which is jointed to the crank *d* on the axle of the driving-wheel *m*. The cranks of the two driving-wheels, one on each side of the engine, are set at right angles to each other, so that, when one is at a dead point, the other is in the most advantageous position. *w* is a spring safety-valve, and J the steam-whistle.

390. Apparatus for Reversing: Link-motion.—The method usually employed for reversing engines is known as Stephenson's link-motion, having been first employed in locomotives constructed by Robert Stephenson, son of the maker of the "Rocket." The merit of the invention belongs to one or both of two workmen in his employ—Williams, a draughtsman, who first designed it, and Howe, a pattern-maker, who, being employed by Williams to construct a model of his invention, introduced some important improvements.

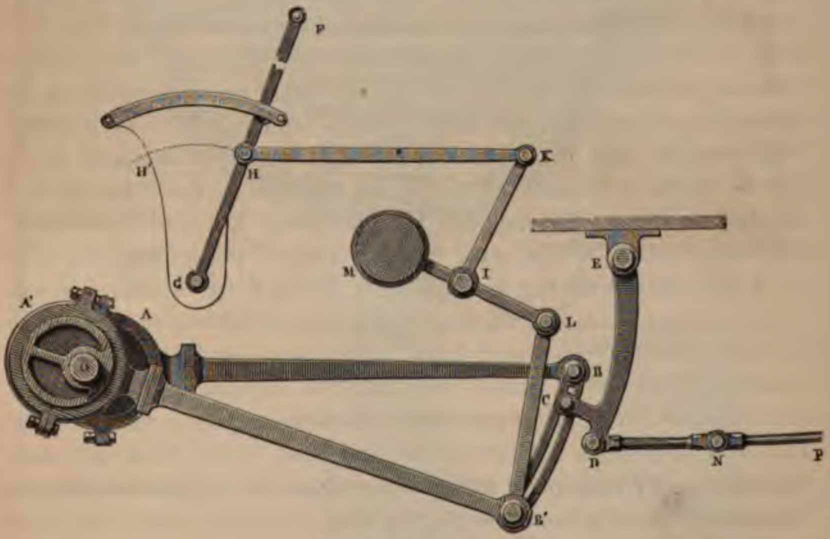


Fig. 330.—Link-motion.

The link-motion, which is represented in Fig. 330, serves two purposes; first, to make the engine travel forwards or backwards at pleasure; and, secondly, to regulate the amount of expansion which shall take place in the cylinder. Two oppositely placed eccentrics, A and A′, have their connecting-rods jointed to the two extremities of the *link* B B′, which is a curved bar, having a slit, of uniform width, extending along nearly its whole length. In this slit travels a stud or button C, forming part of a lever, which turns about a fixed point E. The end D of the lever D E is jointed to the connecting-rod D N, which moves the rod P of the slide-valve. The link itself is connected with an arrangement of rods L I K H,[1] which enables the engine-driver to raise or lower it at pleasure by means of the handle G H F. When the link is lowered to the fullest extent, the end B of the connecting-rod, driven by the eccentric A, is very near the runner C which governs the movement of the slide-valve; this valve, accordingly, which can only move in a straight line, obeys the eccentric A almost exclusively. When the link is raised as much as possible, the slide-valve obeys the other eccentric A′, and this change reverses the engine. When the link is exactly midway between the two extreme positions, the slide-valve is influenced by both eccentrics equally, and consequently remains nearly stationary in its middle position, so that no steam is admitted to the cylinder, and the engine stops. By keeping the link near the middle position, steam is admitted during only a small part of the stroke, and consequently undergoes large expansion. By moving it nearer to one of its extreme positions, the travel of the slide-valve is increased, the ports are opened wider and kept open longer, and the engine will accordingly be driven faster, but with less expansion of the steam. As a means of regulating expansion, the link-motion is far from perfect, but its general advantages are such that it has come into very extensive use, not only for locomotives but for all engines which need reversal.

393. Gas-engines.—This name includes engines in which work is obtained by the expansion of a mixture of coal-gas and air, on ignition or explosion. In Lenoir's engine a piston is driven alternately in opposite directions by successive ignitions of such a mixture on opposite sides of it, the proportions of gas and air being such as not to yield a true explosion.

In the engine of Otto and Langen (Fig. 331), a true explosive mixture is introduced beneath the piston, and is exploded by means

---

[1] I is a fixed centre of motion, and the rods K I, M L are rigidly connected at right angles to each other. M is a heavy piece, serving to counterpoise the link and eccentric rods.

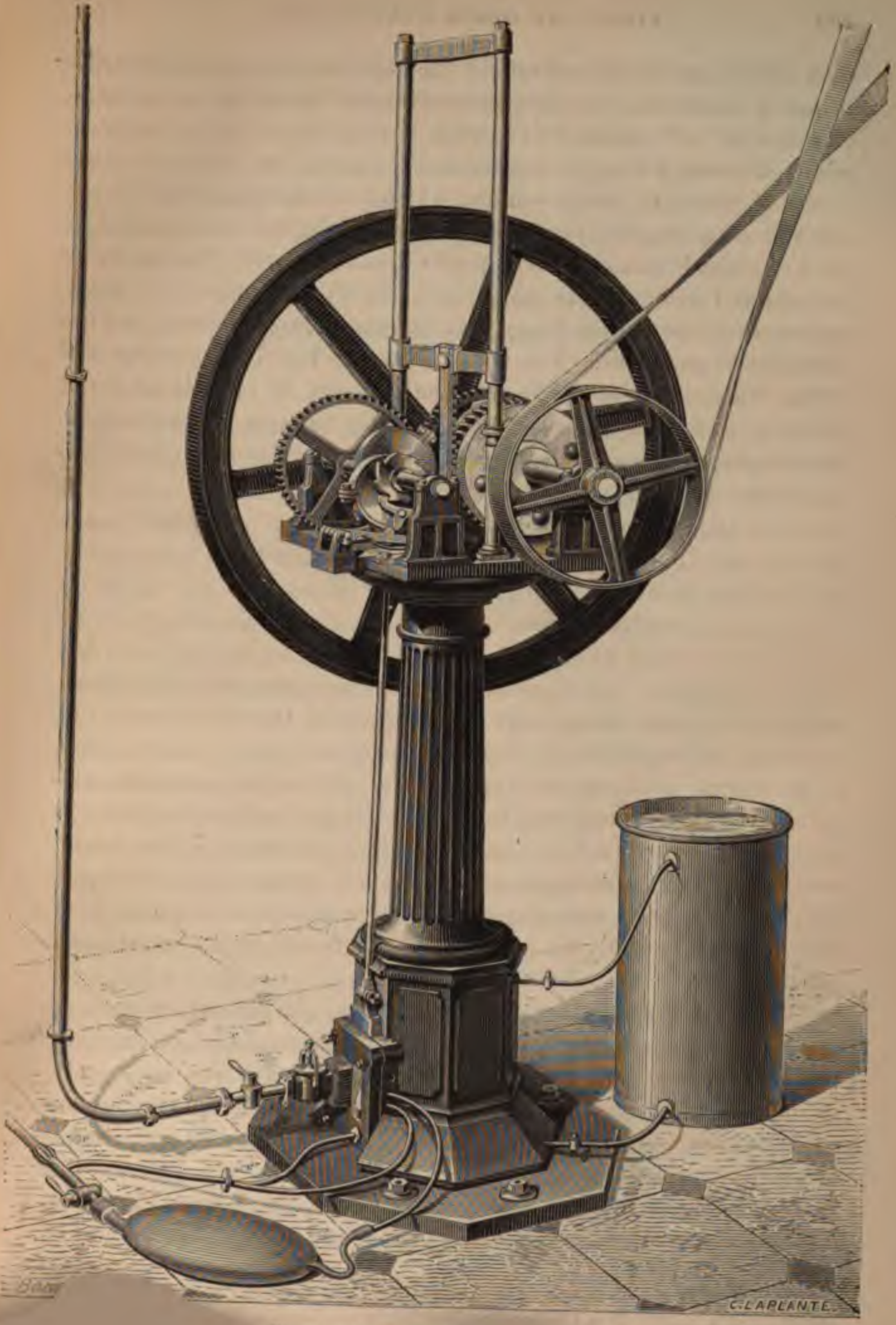


Fig. 331.—Gas-engine of Ott gen.

of a lighted jet, which is brought into contact with the mixture by means of a hole in a movable plate of metal, driven by an eccentric. The upward movement of the piston thus produced is too violent to admit of being directly communicated to machinery. The piston-rod is a rack, working with a pinion, which is so mounted that it can slip round on the shaft when the piston ascends, but carries the shaft with it when it turns in the opposite direction during the descent of the piston, this descent being produced by the pressure of the atmosphere, as the steam resulting from the explosion condenses, and the unexploded gases cool. The vessel shown on the right contains cold water, which is employed to cool the cylinder by circulating round the lower part of it. The quantity of water required for this purpose is much smaller, and the consumption of gas is also much less, than in Lenoir's engine.

CHAPTER XXXIV.

TERRESTRIAL TEMPERATURES.

394. Temperature of the Air.—By the *temperature of a place* meteorologists commonly understand the *temperature of the air* at a moderate distance (5 or 10 feet) from the ground. This element is easily determined when there is much wind; but in calm weather, and especially when the sun is shining powerfully, it is often difficult to avoid the disturbing effect of radiation. Thermometers for observing the temperature of the air must be sheltered from rain and sunshine, but exposed to a free circulation of air.

395. Mean Temperature of a Place.—The *mean temperature of a day* is obtained by making numerous observations at equal intervals of time throughout the day (24 hours), and dividing the sum of the observed temperatures by their number. The accuracy of the determination is increased by increasing the number of observations; as the mean temperature, properly speaking, is the mean of an infinite number of temperatures observed at infinitely short intervals.

If the curve of temperature for the day is given, temperature being represented by height of the curve above a horizontal datum line, the mean temperature is the height of a horizontal line which gives and takes equal areas; or is the height of the middle point of any straight line (terminated by the extreme ordinates of the curve) which gives and takes equal areas.

Attempts have been made to lay down rules for computing the mean temperature of a day from two, three, or four observations at stated hours; but such rules are of very limited application, owing to the different character of the diurnal variation at different places; and at best they cannot pretend to give the temperature of an individual day, but merely results which are correct in the long run. Observations at 9 A.M. and 9 P.M. are very usual in this country; and the [illegible] of the temperatures at these hours is in general a good approximation to the mean temperature of the day. The half-sum of the highest and the lowest temperature in the day, as indicated by maximum and minimum thermometers, is often adopted as the mean temperature. The result thus obtained is usually rather above the true mean temperature, owing to the circumstance that the extreme heat of the day is a more transient phenomenon than the extreme cold of the night. The employment of self-registering thermometers has, however, the great advantage of avoiding errors arising from want of punctuality in the observer. The correction which is to be added or subtracted in order to obtain the true mean from the mean of two observations is called a *correction for diurnal range.* Its amount differs for different places, being usually greatest where the diurnal range itself (§ 113) is greatest.

The *mean temperature of a calendar month* is computed by adding the mean temperatures of the days which compose it, and dividing by their number.

The *mean temperature of a year* is usually computed by adding the mean temperatures of the calendar months, and dividing by 12; but this process is not quite accurate, inasmuch as the calendar months are of unequal length. A more accurate result is obtained by adding the mean temperatures of all the days in the year, and dividing by 365 (or in leap-year by 366).

396. Isothermals.—The distribution of temperature over a large region is very clearly represented by drawing upon the map of this region a series of *isothermal lines;* that is, lines characterized by the property that *all places on the same line have the same temperature.* These lines are always understood to refer to mean annual temperature unless the contrary is stated; but isothermals for particular months, especially January and July, are frequently traced, one serving to show the distribution of temperature in winter, and the other in summer. The first extensive series of isothermals was drawn by Humboldt in 1817, on the basis of a large number of observations collected from all parts of the world; and the additional information which has since been collected has not materially altered the forms of the lines traced by him upon the terrestrial globe. They are in many places inclined at a very considerable angle to the parallels of latitude; and nowhere is this deviation from parallelism more observable than in the neighbourhood of Great Britain, Norway, and Iceland—places in this region having the same mean annual temperature as places in Asia or America lying from 10° to 20° further south.

399. Insular and Continental Climates.—The difference between the temperatures of summer and winter is greatest in the interior of large continents, and smallest in small islands in the midst of the ocean; large masses of water being exceedingly slow in changing their temperature, and powerfully contributing to prevent extremes of temperature from occurring in their neighbourhood. It is common to distinguish in this sense between *continental* climates on the one hand and *insular* or *marine* climates on the other.

Some examples of both kinds are given in the following table. The temperatures are Centigrade:—

MARINE CLIMATES.

	Winter.	Summer.	Difference.
Faroe Islands,	3°·90	11°·60	7°·70
Isle of Unst (Shetland),	4 ·05	11 ·92	7 ·87
Isle of Man,	5 ·59	15 ·08	9 ·49
Penzance,	7 ·04	15 ·83	8 ·79
Helston,	6 ·19	16 ·00	9 ·81

CONTINENTAL CLIMATES.

	Winter.	Summer.	Difference.
St. Petersburg,	− 8°·70	15°·96	24°·66
Moscow,	−10 ·22	17 ·55	27 ·77
Kasan,	−13 ·66	17 ·35	31 ·01
Slatoust,	−16 ·49	16 ·08	32 ·57
Irkutsk,	−17 ·88	16 ·00	33 ·88
Jakoutsk,	−38 ·90	17 ·20	56 ·10

400. Temperature of the Soil at Different Depths.—By employing thermometers with their bulbs buried in the earth, and their stems projecting above, numerous observations have been made of the temperature from day to day at different depths from 1 inch to 2 or 3 feet; and at a few places observations of the same kind have been made by means of gigantic spirit-thermometers with exceedingly strong bulbs, at depths extending to about 25 feet. It is found that variations depending on the hour of the day are scarcely sensible at the depth of 2 or 3 feet, and that those which depend on the time of year decrease gradually as the depth increases, but still remain sensible at the depth of 25 feet, the range of temperature during a year at this depth being usually about 2° or 3° Fahrenheit.

It is also found that, as we descend from the surface, the seasons lag more and more behind those at the surface, the retardation amounting usually to something less than a week for each foot of descent; so that, at the depth of 25 feet in these latitudes, the lowest temperature occurs about June, and the highest about December.

Theory indicates that 1 foot of descent should have about the same effect on diurnal variations as $\sqrt{365}$ that is 19 feet on annual variations; understanding by *sameness of effect* equal *absolute amounts* of lagging and equal *ratios* of diminution.

As the annual range at the surface in Great Britain is usually about 3 times greater than the diurnal range, it follows that the diurnal range at the depth of a foot should be about one-third of the annual range at the depth of 19 feet.

The variations of temperature at the surface are, as every one knows, of a very irregular kind; so that the curve of surface temperature for any particular year is full of sinuosities depending on the accidents of that year. The deeper we go, the more regular does the curve become, and the more nearly does it approach to the character of a simple curve of sines, whose equation can be written

$$y = a \sin. x.$$

Neglecting the departures of the curve from this simple character, theory indicates that, if the soil be uniform, and the surface plane, the annual range (which is equal to $2\,a$) goes on diminishing in geometrical progression as the depth increases in arithmetical; and observation shows that, if 10 feet be the common difference of depth, the ratio of decrease for range is usually about $\frac{1}{2}$ or $\frac{1}{3}$.

To find a range of a tenth of a degree Fahrenheit, we must go to a depth of from 50 to 80 feet in this climate. At a station where the surface range is double what it is in Great Britain, we should find a range of about two-tenths of a degree at a depth and in a soil which would here give one-tenth.

These remarks show that the phrase "stratum of invariable temperature," which is frequently employed to denote the supposed lower boundary of the region in which annual range is sensible, has no precise significance, inasmuch as the boundary in question will vary its depth according to the sensitiveness of the thermometer employed.

401. Increase of Temperature Downwards.—Observations in all parts of the world show that the temperature at considerable depths, such as are attained in mining and boring, is much above the surface temperature. In sinking a shaft at Rose Bridge Colliery, near Wigan, which is the deepest mine in Great Britain, the temperature of the rock was found to be 94° F. at the depth of 2440 feet. In cutting the Mont Cénis tunnel, the temperature of the deepest part, with 5280 feet of rock overhead, was found to be about 85° F.

The rate of increase downwards is by no means the same everywhere; but it is seldom so rapid as 1° F. in 40 feet, or so slow as 1° F. in 100 feet. The observations at Rose Bridge show a mean rate of increase of about 1° in 55 feet; and this is about the average of the results obtained at other places.

This state of things implies a continual escape of heat from the interior of the earth by conduction, and the amount of this loss per annum can be approximately calculated from the absolute values of conductivity of rock which we have given in Chap. xxx.

There can be no reasonable doubt that the decrease of temperature upwards extends to the very surface, when we confine our attention to mean annual temperatures, for all the heat that is conducted up through a stratum at any given depth must also traverse all the strata above it, and heat can only be conducted from a warmer to a colder stratum. Professor Forbes found, at his three stations near Edinburgh, increases of 1°·38, 0°·96, and 0°·19 F. in mean temperature, in descending through about 22 feet, that is, from the depth of 3 to the depth of 24 French feet. The mean annual temperature of the surface of the ground is in Great Britain a little superior to that of the air above it, so far as present observations show. The excess appears to average about 1° F. At Trevandrum in India the excess is in the same direction, and amounts to 5° or 6° F.

402. Decrease of Temperature Upwards in the Air.—In comparing the mean temperatures of places in the same neighbourhood at different altitudes, it is found that temperature diminishes as height increases, the rate of decrease for Great Britain, as regards mean annual temperature, being about 1° F. for every 300 feet. A decrease of temperature upwards is also usually experienced in balloon ascents, and numerous observations have been taken for the purpose of determining its rate. Mr. Glaisher's observations, which are the most numerous as well as the most recent, show that, upon the whole, the decrease becomes less rapid as we ascend higher; also, that it is less rapid with a cloudy than with a clear sky. The following table exhibits a few of Mr. Glaisher's averages:—

	Decrease of Temperature Upwards.	
Height.	With clear sky.	With cloudy sky
From 0 to 1000 feet, . . .	1° F. in 139 feet.	1° F. in 222 feet.
From 0 to 10,000 ft. . . .	1° F. in 288 feet.	1° F. in 331 feet.
From 0 to 20,000 ft. . . .	1° F. in 365 feet.	1° F. in 468 feet.

These rates may be taken as representing the general law of decrease which prevails in the air over Great Britain in the daytime during the summer half of the year; but the results obtained on different days differ widely, and alternations of increase and decrease are by no means uncommon in passing upwards through successive strata [illegible] Still more recent obser[illegible] by Mr. Glaisher, relating chiefly to the first 1000 feet of air, show that the law varies with the hour of the day. The decrease upwards is most rapid soon after midday, and is at this time, and during daytime generally, more rapid as the height is less. About sunset there is a uniform *decrease* at all heights if the sky is clouded, and a uniform *temperature* if the sky is clear. From a few observations which have been taken after sunset, it appears that, with a clear sky, there is an *increase* upwards at night.

That an extremely low temperature exists in the interplanetary spaces, may be inferred from the experimental fact recorded by Sir John Herschel, that a thermometer with its bulb in the focus of a reflector of sufficient size and curvature to screen it from lateral radiation, falls lower when the axis of the reflector is directed upwards to a clear sky than when it is directed either to a cloud or to the snow-clad summits of the Alps. The atmosphere serves as a protection against radiation to these cold spaces, and it is not surprising that, as we increase our elevation, and thus diminish the thickness of the coating of air above us, the protection should be found less complete.

403. Cooling of an Ascending Column of Air.—Whenever a body of air ascends, it expands, in consequence of the diminution of pressure; and the work which it does in expanding consumes a portion of its heat, and lowers its temperature. In like manner, when air descends, the work done upon it in compressing it raises its temperature. The amount of this change of temperature can be at once inferred from § 347A, by putting $t = 1^\circ$ C., $\alpha = \cdot 00366$, $\beta = \cdot 41$. In fact, a compression or expansion amounting to ·00366 of the volume which the air would occupy at zero, alters its temperature by 0·41° C. Consequently, for an alteration of 1° C., we must have a change of volume amounting to ·00893, which, in conjunction with the change of temperature, implies a change of pressure amounting to $\cdot 00893 + \cdot 00366 = \cdot 0126 = \frac{1}{80}$ of the actual pressure. This corresponds to an ascent or descent through $\frac{1}{80}$ of the height of a homogeneous atmosphere (§ 111A), that is, through about 330 feet. For a change of 1° F., the required height will be 183 feet. These numbers are computed on the assumption that the air is sufficiently dry to behave like a permanent gas. If ascending air contains vapour which is condensed by the loss of heat, this condensation greatly retards the cooling; and if descending air contains mist which is dissipated by the gain of heat, this dissipation retards the warming.

It is obvious that the ascent of warm air will not occur, unless the actual decrease of temperature upwards is more rapid than the cooling due to ascent; for air will not rise if the process of rising would make it colder and heavier than the air through which it would have to pass.

404. Causes of Winds.—The influences which modify the direction and intensity of winds are so various and complicated that anything like a complete account of them can only find a place in treatises specially devoted to that subject. There is, however, one fundamental principle which suffices to explain the origin of many well-known winds. This principle is plainly illustrated by the following experiment, due to Franklin. A door between two rooms, one heated, and the other cold (in winter), is opened, and two candles are placed, one at the top, and the other at the bottom of the doorway. It is found that the flame of the lower candle is blown towards the heated room, and that of the upper candle away from it.

From this experiment we can deduce the following general principle:—*When two neighbouring regions are at different temperatures, a current of air flows from the warmer to the colder in the upper strata of the atmosphere; and in the lower strata a current flows from the colder to the warmer.* We proceed to apply this principle to the land and sea breezes, the monsoons, and the trade-winds.

405. Land and Sea Breezes.—At the sea-side during calm weather a wind is generally observed to spring up at about eight or nine in the morning, blowing from the sea, and increasing in force until about two or three in the afternoon. It then begins gradually to die away, and shortly before sunset disappears altogether. A few hours afterwards, a wind springs up in the opposite direction, and lasts till nearly sunrise. These winds, which are called the sea-breeze and land-breeze, are exceedingly regular in their occurrence, though they may sometimes be masked by other winds blowing at the same time. Their origin is very easily explained. During the day the land grows warmer than the water; hence there results a wind blowing towards the warmer region, that is, towards the land. During the night the land and sea both grow colder, but the former more rapidly than the latter; and, accordingly, the relative temperatures of the two elements being now reversed, a breeze blowing from the land towards the sea is the consequence.

Monsoons.—The same cause which, on a small scale, produces the diurnal alternation of land and sea breezes, produces, on a larger scale, th[illegible]al alternation of monsoons in th[illegible]lian Ocean, and the s[illegible]hich prevail in some oth[illegible]of the world. The general direction of these winds is towards continents in summer, and away from them in winter.

406. Trade-winds: General Atmospheric Circulation.—The trade-winds are winds which blow constantly from a north-easterly quarter over a zone of the northern hemisphere extending from a little north of the tropic of Cancer to within 9 or 10 degrees of the equator; and from a south-easterly quarter over a zone of the southern hemisphere extending from about the tropic of Capricorn to the equator. Their limits vary slightly according to the time of year, changing in the same direction as the sun's declination. Between them is a zone some 5° or 6° wide, over which calms and variable winds prevail.

The cause of the trade-winds was first correctly indicated by Hadley. The greater power of the sun over the equatorial regions causes a continual ascent of heated air from them. This flows over to both sides in the upper regions of the atmosphere, and its place is supplied by colder air flowing in from both sides below. If the earth were at rest, we should thus have a north wind sweeping over the earth's surface on the northern side of the equatorial regions, and a south wind on the southern side. But, in virtue of the earth's rotation, all points on the earth's surface are moving from west to east, with velocities proportional to their distances from the earth's axis. This velocity is nothing at the poles, and increases in approaching the equator. Hence, if a body on the earth's surface, and originally at rest relatively to the earth, be urged by a force acting along a meridian, it will not move along a meridian, but will outrun the earth, or fall behind it, according as its original rotational velocity was greater or less than those of the places to which it comes. That is to say, it will have a relative motion from the west if it be approaching the pole, and from the east if it be approaching the equator.

This would be true, even if the body merely tended to keep its original rotational velocity unchanged, and the reasoning becomes still more forcible when we apply the principle of conservation of angular momentum (§§ 53 F, G), in virtue of which the body tends to increase[1] its absolute rotational velocity in approaching the pole, and to diminish it in approaching the equator.

Thus the currents of air which flow in from both sides to the equatorial regions, do not blow from due north and due south, but from north-east and south-east. There can be little doubt that, notwithstanding the variable character of the winds in the temperate and frigid zones, there is, upon the whole, a continual interchange of air between them and the intertropical regions, brought about by the permanent excess of temperature of the latter. Such an interchange, when considered in conjunction with the difference in the rotational velocities of these regions, implies that the mass of air over an equatorial zone some 50° or 60° wide, must, upon the whole, have a relative motion from the east; and that the mass of air over all the rest of the earth must, upon the whole, have a relative motion from the west. This theoretical conclusion is corroborated by the distribution of barometric pressure. The barometer stands highest at the two parallels which, according to this theory, form the boundaries between easterly and westerly winds, while at the equator and poles it stands low. This difference may be accounted for by the excess of centrifugal force possessed by west winds, and the defect of centrifugal force in east winds. If the air simply turned with the earth, centrifugal force combined with gravity would not tend to produce accumulation of air over any particular zone, the ellipticity of the earth being precisely adapted to an equable distribution. But if a body of air or other fluid is moving with sensibly different rotational velocity from the earth, the difference in centrifugal force will give a tendency to move towards the equator, or from it, according as the differential motion is from the west or from the east. The easterly winds over the equatorial zone should therefore tend to remove air from the equator and heap it up at the limiting parallels; and the westerly winds over the remainder of the earth should tend to draw air away from the poles and heap it up at the same limiting parallels. This theoretical consequence exactly agrees with the following table of mean barometric heights in different zones given by Maury:[1]—

---

[1] The tendency is for velocity to vary inversely as distance from the axis of rotation.

North Latitude.	Barometer.	South Latitude.	Barometer.
0° to 5°	29·915	0° to 5°	29·940
5° to 10°	29·922	5° to 10°	29·981
10° to 15°	29·964	10° to 15°	30·028
15° to 20°	30·018	15° to 20°	30·060
20° to 25°	30·081	20° to 25°	30·102
25° to 30°	30·149	25° to 30°	30·095
30° to 35°	30·210	30° to 36°	30·052
35° to 40°	30·124	42° 53′	29·90
40° to 45°	30·077	45° 0′	29·66
45° to 50°	30·060	49° 8′	29·47
51° 29′	29·99	51° 33′	29·50
59° 51′	29·88	54° 26′	29·35
78° 37′	29·759	55° 52′	29·36
		60° 0′	29·11
		66° 0′	29·08
		74° 0′	28·93

---

[1] *y and Meteorology* 180, art. 362, edition 1860.

This table shows that the barometric height falls off regularly on both sides from the two limiting zones 30° to 35° N. and 20° to 25° S., the fall continuing towards both poles as far as the observations extend, and continuing inwards to a central minimum between 0° and 5° N.[1]

If the bottom of a cylindrical vessel of water be covered with saw-dust, and the water made to rotate by stirring, the saw-dust will be drawn away from the edges, and heaped up in the middle, thus showing an indraught of water along the bottom towards the region of low barometer in the centre. It is probable that, from a similar cause (a central depression due to centrifugal force), there is an indraught of air along the earth's surface towards the poles, underneath the primary circulation which our theory supposes; the diminution of velocity by friction against the earth, rendering the lowest portion of the air obedient to this indraught, which the upper strata are enabled to resist by the centrifugal force of their more rapid motion. This, according to Professor James Thomson,[2] is the explanation of the prevalence of south-west winds in the north temperate zone; their southerly component being due to the barometric indraught and their westerly component to differential velocity of rotation. The indraught which also exists from the limiting parallels to the region of low barometer at the equator, coincides with the current due to difference of temperature; and this coincidence may be a main reason of the constancy of the trade-winds.

406 A. Origin of Cyclones.—In the northern hemisphere a wind which would blow towards the north if the earth were at rest, does actually blow towards the north-east; and a wind which would blow towards the south blows towards the south-west. In both cases, the earth's rotation introduces a component towards the right with reference to a person travelling with the wind. In the southern hemisphere it introduces a component towards the left.

Again, a west wind has an excess of centrifugal force which tends to carry it towards the equator, and an east wind has a tendency to move towards the pole; so that here again, in the northern hemisphere the deviation is in both cases to the right, and in the southern hemisphere to the left.

---

[1] The explanation here given of the accumulation of air towards the limiting parallels, as due to excess and defect of centrifugal force, appears to have been first published by Mr. W. Ferrel, a gentleman connected with the American Nautical Almanack. His later treatise (1860), reprinted from vols. i. ii. of the *Mathematical Monthly*, is the most com[illegible] exposition we have seen of the theory of general atmospheric circulation.

[2] *Brit. Assoc. Report*, 1857.

We have thus an explanation of cyclonic movements. In the northern hemisphere, if a sudden diminution of pressure occurs over any large area, the air all round for a considerable distance receives an impetus directed towards this area. But, before the converging streams can meet, they undergo deviation, each to its own right, so that, instead of arriving at their common centre, they blow tangentially to a closed curve surrounding it, and thus produce an eddy from right to left with respect to a person standing in the centre. This is the universal direction of cyclonic rotation in the northern hemisphere; and the opposite rule holds for the southern hemisphere. The former is opposite to, the latter the same as the direction of motion of the hands of a watch lying with its face up. In each case the motion is opposite to the apparent diurnal motion of the sun for the hemisphere in which it occurs.

407. Anemometers.—Instruments for measuring either the force or the velocity of the wind are called *anemometers.* Its force is usually measured by Osler's anemometer, in which the pressure of the wind is received upon a square plate attached to one end of a spiral spring (with its axis horizontal), which yields more or less according to the force of the wind, and transmits its motion to a pencil which leaves a trace upon paper moved by clock-work. It seems that the force received by the plate is not rigorously proportional to its size, and that a plate a yard square receives rather more than 9 times the pressure of a plate a foot square. The anemometer which has yielded the most satisfactory results is that invented by the Rev. Dr. Robinson of Armagh, which is represented in Fig. 331 A, and which indicates the velocity of the wind. It consists of four hemispherical cups attac [illegible] ends of equal horizontal arms, forming a horizontal

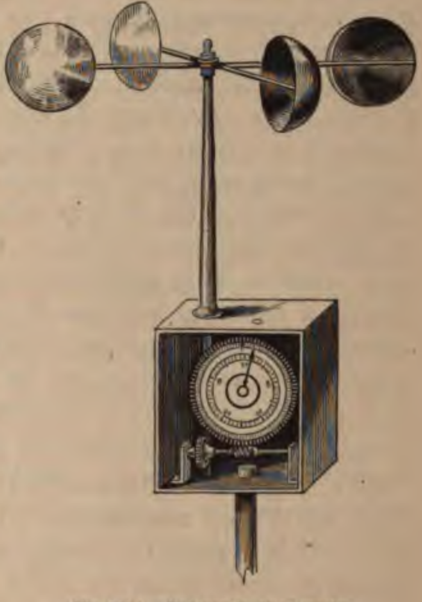


Fig. 331 A.—Robinson's Anemometer.

cross, which turns freely about a vertical axis. By means of an endless screw carried by the axis, a train of wheel-work is set in motion; and the indication is given by a hand which moves round a dial; or, in some instruments, by several hands moving round different dials like those of a gas-meter. The anemometer can also be made to leave a continuous record on paper, for which purpose various contrivances have been successfully employed. It was calculated by the inventor, and confirmed by his own experiments both in air and water, as well as by experiments conducted by Prof. C. Piazzi Smyth at Edinburgh, and more recently by the astronomer-royal at Greenwich, that the centre of each cup moves with a velocity which is almost exactly one-third of that of the wind. This is the only velocity-anemometer whose indications are exactly proportional to the velocity itself. Dr. Whewell's anemometer, which resembles a small windmill, is very far from fulfilling this condition, its variations of velocity being much less than those of the wind.

The direction of the wind, as indicated by a vane, can also be made to leave a continuous record by various contrivances; one of the most common being a pinion carried by the shaft of the vane, and driving a rack which carries a pencil. But perhaps the neatest arrangement for this purpose is a large screw with only one thread composed of a metal which will write on paper. A sheet of paper is moved by clock-work in a direction perpendicular to the axis of the screw, and is pressed against the thread, touching it of course only in one point, which travels parallel to the axis as the screw turns, and comes back to its original place after one revolution. When one end of the thread leaves the paper, the other end at the same instant comes on. The screw turns with the vane, so that a complete revolution of the screw corresponds to a complete revolution of the wind. This is one of the many ingenious contrivances devised and executed by Mr. Beckley, mechanical assistant in Kew Observatory.

Bb.